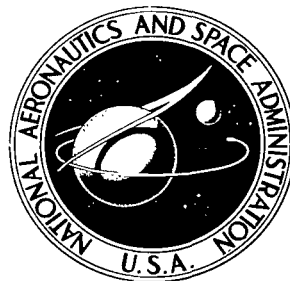


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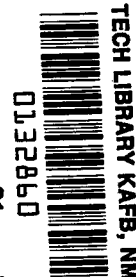


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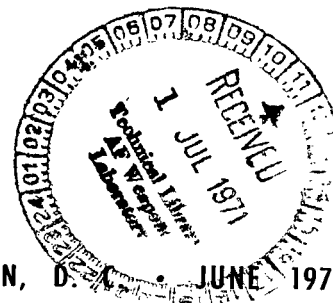
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COMPARISON OF SIMPLEX
AND DUAL-ORIFICE FUEL NOZZLES
WITH AMBIENT AND HEATED FUEL
IN AN ANNULAR TURBOJET COMBUSTOR

*by Donald F. Schultz, Jerrold D. Wear,
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1971



0132860

1. Report No. NASA TN D-6355		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle COMPARISON OF SIMPLEX AND DUAL-ORIFICE FUEL NOZZLES WITH AMBIENT AND HEATED FUEL IN AN ANNULAR TURBOJET COMBUSTOR				5. Report Date June 1971	
				6. Performing Organization Code	
7. Author(s) Donald F. Schultz, Jerrold D. Wear, and Porter J. Perkins				8. Performing Organization Report No. E-5999	
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135				10. Work Unit No. 720-03	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546				13. Type of Report and Period Covered Technical Note	
				14. Sponsoring Agency Code	
15. Supplementary Notes					
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17. Key Words (Suggested by Author(s)) Jet engine, Combustors, Combustion, Hydrocarbon combustion, Combustion efficiency, and Ignition limits				18. Distribution Statement Unclassified - unlimited	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 36	
				22. Price* \$3.00	

COMPARISON OF SIMPLEX AND DUAL-ORIFICE FUEL NOZZLES WITH AMBIENT AND HEATED FUEL IN AN ANNULAR TURBOJET COMBUSTOR

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SUMMARY

A full-scale annular combustor was operated with simplex fuel nozzles selected to give finely atomized fuel sprays over three different ranges of fuel flow. Comparative combustor performance data were also obtained with dual-orifice fuel nozzles. The dual-orifice nozzles provided combustion efficiencies within 2 to 3 percent of the peak values obtained with any of the simplex atomizers over the entire range of test conditions. A wide range of operating conditions including altitude relight, simulated takeoff, Mach 2.7 cruise, and Mach 3.0 cruise were studied. Measurements were made of combustion efficiency, pattern factor, flame radiation, smoke emission, and response to rapid increase in fuel flow. Fuel heated to 300⁰ F (423 K) was used in many of the tests; heated fuel usually increased combustion efficiency.

INTRODUCTION

Previous research investigations of jet engine combustors (refs. 1 to 3) have used simplex fuel nozzles in lieu of the more complex and expensive dual-orifice nozzles which would be required in practical aircraft gas turbine usage. The research reported herein was conducted with a full-annulus ram-induction combustor in a connected-pipe facility to determine the following: (1) the performance attainable with finely atomized fuel sprays obtained by means of simplex nozzles selected to give good atomization over three different ranges of fuel flow rate, (2) the performance of the same combustor with dual-orifice nozzles, (3) the combustor performance with dual-orifice nozzles compared with the peak levels obtained with the various simplex nozzles, and (4) the effects of fuel inlet temperature on combustor performance with both types of nozzles. The combustor performance measurements included combustion efficiency, exit-temperature

pattern factor, altitude relight limits, combustor response to rapid fuel flow increases, flame radiation, and smoke emission.

FACILITY

The fuel nozzle comparison investigation was conducted in a closed-duct test facility of the Engine Components Research Laboratory of the Lewis Research Center. A block diagram of this facility is shown in figure 1. Airflows for combustion could be heated to 1200⁰ F (922 K) without vitiation before entering the combustor.

Airflow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the test section. Flow straighteners were used to evenly distribute the airflow entering the combustor. The fuel was heated in the heated-fuel tests in a steam-fed heat exchanger. Up to 3900 pounds per hour (0.49 kg/sec) of ASTM-A1 fuel could be heated to 300⁰ F (422 K) at a maximum fuel pressure of 320 psig (230 N/cm²) with this heat exchanger. Further details of the facility and instrumentation can be found in figure 1 and references 2 and 3.

CALCULATIONS

Combustion efficiency was determined by dividing the measured temperature rise across the combustor by the theoretical temperature rise. The exit temperatures were measured with five-point traversing aspirated thermocouple probes and were mass weighted for the efficiency calculation. In each mass-weighted average, 585 individual exit temperatures were used.

The total-pressure loss was calculated by mass-averaging 40 total pressures measured upstream of the diffuser inlet and 585 pressures at the combustor exit. The total-pressure loss therefore includes the diffuser loss.

The Mach numbers were determined from 16 inlet static pressures measured around the inlet annulus, the inlet annulus area, and the measured airflow.

TEST COMBUSTOR

The combustor tested was designed using the ram-induction approach described in references 1 and 2. With this approach the compressor discharge air is diffused less than it is in conventional combustors. The relatively high-velocity air is then captured by scoops in the combustor liner and turned into the combustion and mixing zones.

Vanes are used in the scoops to reduce pressure loss caused by the high-velocity turns. The high velocity and steep angle of the entering air jets promote rapid mixing of the fuel and air in the combustion zone and of the burned gases and air in the dilution zone. The potential result of the rapid mixing is a shorter combustor or, alternatively, a better exit-temperature profile in the same length.

A cross section of the combustor is shown in figure 2. The outer diameter is almost 42 inches (1.07 m) and the length from compressor exit to turbine inlet is approximately 30 inches (0.76 m). A snout (fig. 2) on the combustor divides the diffuser into three concentric annular passages. The central passage conducts air to the combustor headplate and the inner and outer passages supply air to the combustor liners. There are five rows of scoops on each of the inner and outer liners to turn the air into the combustion and dilution zones.

The snout and the combustor liners are shown in figure 3. Figure 3(a) is a view looking upstream into the combustor liner. The scoops in the inner and outer liner can be seen, as well as the openings in the headplate for the fuel nozzles and swirlers. Figure 3(b) is a view of the snout and the upstream end of the combustor liner. The V-shaped cutouts in the snout fit around struts in the diffuser. The circular holes through the snout walls are for the fuel nozzle struts. Figure 3(c) gives a closer view of the liner and headplate, showing the 24 fuel nozzles and swirlers in place. Further details of the combustor design are given in reference 4.

FUEL NOZZLES

Figure 4(a) shows a typical assembly of a simplex nozzle with fuel strut and air swirler. The dual-orifice nozzle fit the same fuel strut and air swirler. Cross sections of a dual-orifice nozzle and a simplex nozzle are shown in figures 4(b), and 4(c) respectively.

The fuel flow against fuel nozzle differential pressure is shown in figure 5 for the three sizes of simplex and the one size of dual-orifice nozzles tested. The ambient-temperature fuel characteristic is shown with solid lines for each nozzle while the heated (300° F, 423 K) fuel characteristic is shown with a dashed line. The number 1 simplex nozzles were not used with heated fuel. Of note is the characteristic of the heated fuel flow compared to the ambient fuel flow with the dual-orifice fuel nozzles. On the simplex portion of the dual-orifice curve, heated fuel increases the differential pressure necessary for any given flow, the same as with the simplex nozzles. But heating decreases the differential pressure required for a given fuel flow once the nozzle pintle has begun to open. This is viewed as an academic observation rather than a physical problem. The point on the curve where the pintle opens is referred to as the "knee" of the flow curve.

The three simplex nozzles were sized so that all operating conditions could be met without operating below 50-psid (34.4-N/cm^2) fuel nozzle differential pressure. Fuel nozzle differential pressure less than 50 psid (34.4 N/cm^2) can cause a loss in combustion efficiency due to poor fuel atomization. The fuel nozzles covered the ranges shown in table I with a minimum differential pressure of 50 psid (34.4 N/cm^2) and a maximum of about 900 psid (620 N/cm^2).

In this investigation, where air well above the coking temperature of the fuel could be flowing past the fuel nozzles for extended periods of time, gaseous nitrogen was used to purge all the fuel from the fuel manifolds and nozzles whenever fuel flow was turned off. A gaseous-nitrogen purge flow rate of about 0.027 pound per second (0.012 kg/sec) was sufficient to clear the system of fuel when the simplex nozzles were used. Over 700 hours of running time were logged with this combustor with no simplex nozzle problems once an adequate nitrogen flow was supplied.

The dual-orifice nozzles, having moving parts, posed the additional problem of nozzle cooling as well as purging. In an engine installation this would be no problem, for as soon as the engine was shut down the inlet-air temperature would quickly drop off to a safe level. However, the test facility cannot react this quickly. Therefore, a minimum nitrogen purge flow of 0.24 pound per second (0.11 kg/sec) was necessary to provide enough nozzle cooling to prevent nozzles from sticking or developing hysteresis. Approximately 28 hours were logged using this purge flow with the dual-orifice nozzles.

RESULTS AND DISCUSSION

Table II(a) to (d) presents the computed test data used in this report.

Simplex - Dual-Orifice Nozzle Comparison with Ambient-Temperature Fuel

Simplex and dual-orifice fuel nozzles were compared on the basis of combustion efficiency, pattern factor, blowout and relight performance, combustor response to rapid increase in fuel flow, flame radiation, smoke emission, and fuel nozzle durability. To magnify the performance differences between the fuel nozzle types, most tests were at off-design conditions. The only design engine conditions tested were the simulated takeoff, Mach 2.7 cruise, Mach 3.0 cruise, and the altitude relight performance. These engine conditions are defined in table III.

Combustion efficiency. - At combustor operating conditions such as inlet-air total temperatures of 600° to 1150° F (589 to 895 K), inlet total pressures of 40 to 90 psia

(27.6 to 62.0 N/cm²), and reference velocities of 100 to 150 feet per second (30.5 to 45.7 m/sec), both types of fuel nozzles performed at 100 percent combustion efficiency over the range of fuel-air ratios tested.

Figure 6(a) shows combustion efficiency for the two types of fuel nozzles at various inlet-air temperatures. As can be seen there is little difference in combustion efficiency between the two nozzle types at constant fuel-air ratio. Also shown on this figure is the effect of fuel-air ratio on efficiency with inlet-air temperature below 600° F (589 K).

The data presented in figure 6(b) for the dual-orifice nozzle fuel-air ratio range is typical for simplex nozzles as well. The combustor would flame out before reaching a fuel-air ratio of 0.021 at 75° F (297 K). Thus, the 0.021 fuel-air ratio curve on figure 6(b) apparently crosses the 0.012 fuel-air ratio curve somewhere between an inlet-air temperature of 75° F (297 K) and 250° F (394 K).

The variation of combustion efficiency with inlet-air total pressure is shown in figure 7. There is little difference in efficiency between simplex and dual-orifice fuel nozzles within the span of experimental error (figs. 7(a) and (b)). Since low fuel nozzle differential pressure can also cause a loss in combustion efficiency due to poor fuel atomization, test points with a fuel nozzle differential pressure less than 50 psid (34.4 N/cm²) have been identified with a flag. Since there is little difference in efficiency between the two nozzle types, dual-orifice fuel nozzles are a satisfactory substitute for simplex nozzles and a single set of nozzles can cover the full range of fuel flows required.

Shown in figure 7(c) is the effect of fuel-air ratio on combustion efficiency at low pressure. These data indicate that a loss in efficiency of 1 to 3 percent can be expected by reducing the fuel-air ratio from 0.022 to 0.011. Since similar results were obtained using simplex nozzles, the conclusions that dual-orifice nozzles are satisfactory is still valid.

Figure 8, showing combustion efficiency at various fuel nozzle differential pressures, indicates that combustion efficiency increases with increasing fuel nozzle differential pressure. Lines of constant fuel-air ratio are drawn between the simplex nozzle types. It is reasonable to assume that a similar simplex nozzle with a fuel-flow-against-fuel-nozzle differential pressure characteristic falling between the number 2 and number 3 simplex nozzles (fig. 5) would have combustion efficiency - differential pressure points that would plot on the given fuel-air ratio lines, one point for each line (fig. 8).

In like manner if a dual orifice nozzle was to be comparable to a simplex nozzle in this differential pressure range, it would have to produce a combustion efficiency equal to a simplex nozzle which had the same flow-against-differential-pressure characteristic as the dual-orifice nozzle. That is, the combustion efficiency - differential pressure points for the dual-orifice nozzles must fall on the constant fuel-air ratio lines drawn

between the simplex points. As can be seen in figure 8 the dual-orifice points do in fact fall on the simplex lines of constant fuel-air ratio. This demonstrates that comparable performance is obtained with both fuel nozzle types.

Exit-temperature profile. - The desired average radial distribution of temperature at the combustor exit plane is determined by the stress and cooling characteristics of the turbine. For purposes of evaluating the combustor, an exit radial temperature profile was selected for conditions that are typical of advanced engines. Figure 9, a plot of average radial and maximum radial temperature, shows that the exit-temperature profile distribution is not affected by the choice of fuel nozzle type. The maximum and average values of temperature for the nozzles tested are all very closely grouped.

Exit-temperature profile is evaluated in terms of pattern factor $\bar{\delta}$ defined as

$$\bar{\delta} = \frac{T_{\text{exit, max}} - T_{\text{exit, av}}}{T_{\text{exit, av}} - T_{\text{inlet, av}}}$$

where $T_{\text{exit, max}} - T_{\text{exit, av}}$ is the maximum temperature occurring anywhere in the combustor exit plane minus the average exit temperature, and $T_{\text{inlet, av}}$ is the average inlet temperature.

Figure 10 presents pattern factor data at various combustor temperature rises for three simulated engine operating levels using simplex and dual-orifice fuel nozzles. Figure 10(a) presents data at a simulated takeoff condition where the engine would be operated at 90.0-psia (62.0-N/cm²) inlet total pressure, 600° F (589 K) inlet-air total temperature, and 100-foot-per-second (30.5-m/sec) reference velocity. In this case the pattern factors obtained with the number 2 simplex and dual-orifice nozzles are nearly identical, while the number 1 simplex nozzles gave higher values. Figure 10(b) and (c) are simulated cruise conditions which are at 60-psia (41.4-N/cm²) inlet-air total pressure, 1050° F (840 K) inlet-air total temperature, 140-foot-per-second (42.7-m/sec) reference velocity for a Mach 2.7 cruise and 90-psia (62-N/cm²) inlet-air total pressure, 1150° F (894 K) inlet-air total temperature, 150-foot-per-second (45.7-m/sec) reference velocity for a Mach 3.0 cruise, respectively. In these figures the number 1 simplex and dual-orifice nozzles gave very similar results.

Further pattern factor data are given in the section Additional Tests.

Simplex-Dual-Orifice Nozzle Comparison with Heated Fuel

Figures 11(a) to (c) show the improvement in combustion efficiency for each type fuel nozzle when the fuel is heated. In each case the improvement in efficiency is greater when heated fuel is used with ambient-temperature inlet air than with heated air.

The lower efficiencies of the number 2 simplex nozzles (fig. 11(a)) compared to the number 3 simplex (fig. 11(b)) is probably the result of the lower fuel nozzle differential pressures present with the number 2 simplex nozzles.

Figures 12(a) to (c) show the effect of ambient and heated fuel with dual-orifice nozzle at 60° , 305° , and 590° F (289, 425, and 584 K) inlet-air temperatures with a 133-foot-per-second (40.5 m/sec) reference velocity. These are different inlet conditions than those in figure 11(c). In these figures the combustion efficiency is plotted against combustor average temperature rise.

The data of figures 12(a) to (c) are replotted as a function of fuel-air ratio in figures 13(a) to (c). By comparing figures 12(a) and 13(a), the low inlet-air temperature conditions, it can be seen that at this operating condition the combustor average temperature rise decreases with increasing fuel-air ratio. Also these figures illustrate that heated fuel does not always increase combustion efficiency, which was the case in figure 11(c) and the other curves in figures 12(b) to (c) and 13 (b) to (c).

The effect on combustion efficiency of heating the inlet air or fuel in terms of their enthalpy is shown in figure 14. In the figure, a weighting term Δh_a is the change in enthalpy of the air and Δh_f is the change in enthalpy of the fuel. The effects of adding heat to either or both the inlet-air and fuel is important in determining the overall cycle efficiency of an engine.

An example of the heat input tradeoffs (between heating the air or heating the fuel) representing an increase in combustion efficiency by heating the fuel is seen in figure 14(b) (which is an expansion of area A, fig. 14(a)). Figure 14(b) shows two data points and a dashed line representing an 0.009 fuel-air ratio. One data point was with ambient-temperature fuel at an enthalpy level of 59 Btu per pound of air (137 J/g of air), and the other data point was at the same air condition as the first but the fuel temperature was increased to 300° F (422 K). The heat addition to the fuel increased the system enthalpy 1.0 Btu per pound of air (2.3 J/g of air) and increased the combustion efficiency by 5.5 percent.

To obtain a 5.5 percent increase in combustion efficiency by heating the air instead of the fuel would require an increase of 16 Btu per pound (37.2 J/g) of heat to the air when beginning at the 59-Btu-per-pound-of-air (137-J/g-of-air) point. This is seen by following the 0.009-fuel-air-ratio curve of figure 14(b) from the 59-Btu-per-pound-of-air (137-J/g-of-air) data point until an increase of 5.5 percentage points in combustion efficiency is reached. At this point the air enthalpy has changed 16 Btu per pound (37.2 J/g).

An example of an equal improvement in combustion efficiency by heating either the air or the fuel is also shown in figure 14(b). By beginning on the 0.016-fuel-air-ratio curve (solid line), at the 59-Btu-per-pound-of-air (137-J/g-of-air) point, the addition of 1.7 Btu per pound of air (4.0 J/g of air) to either the air or the fuel results in a com-

bustion efficiency increase of 1 percentage point. Note that the heated-fuel point which is at the same air conditions as the 59-Btu-per-pound-of-air (137-J/g-of-air) point falls on the ambient-temperature fuel curve.

An example of a loss in combustion efficiency when the fuel is heated is shown in figure 14(c) (an expansion of area B of fig. 14(a)). Two data points are shown on this figure - one with ambient-temperature fuel at 0.0 Btu per pound of air (0.0 J/g of air) on the 0.016-fuel-air-ratio, ambient-temperature fuel curve and one point at the same air condition but with 1.7 Btu per pound of air (4.0 J/g of air) added to the fuel. In this case adding heat to the fuel reduced the combustion efficiency 3 percentage points. If this heat had been added to the air instead of the fuel, a rise in combustion efficiency of 2 percentage points would have resulted. This can be seen by reading the difference in combustion efficiency at 0.0 Btu per pound of air (0.0 J/g of air) and at 1.7 Btu per pound of air (4.0 J/g of air). These results may not be typical of other combustor systems.

Additional Tests

Exit-temperature profile. - Pattern factors are shown for some off-design conditions in figures 15(a) and (b). Here the effects of heated fuel can be observed, as well as the "knee" in the fuel-flow-against-fuel-nozzle differential pressure characteristic of the dual-orifice nozzle (fig. 5). Figure 15(a) indicates that heated fuel generally decreases pattern factor at ambient air temperature, 18 psia (12.4 N/cm^2) pressure, and 600° F (589 K) inlet-air temperature. Obviously, care must be taken to avoid operating an engine for extended periods at the knee of a dual-orifice fuel nozzle. This region is denoted by the shaded area shown in the figures. Ground idle operation may be a point of concern.

Also to be noted is the reduction in pattern factor of all the nozzles as a result of increasing the inlet-air temperature as shown in figures 15(a) and (b). This is most likely due to the increase in combustion efficiency with increase in inlet-air temperature (see fig. 6). A decrease in combustion efficiency tends to increase pattern factor.

Blowout and relight tests. - To obtain blowout data, the combustor was first operated at conditions that ensured ignition. Then the pressure was lowered in steps while the inlet-air temperature and reference Mach number were held constant. At each pressure level a burst test (rapid increase in fuel-air ratio) was made to determine whether or not the combustor would produce a corresponding temperature rise. The pressure would then be reduced a further step and the process repeated until the combustor would blowout. A relight was then attempted at successively increased pressure levels. If relight occurred, another burst test was conducted at that condition. Testing was

limited by the facility to a minimum combustor pressure of 4.5 psia (3.1 N/cm^2) at the time when the simplex fuel nozzles were tested, and 3.0 psia (2.1 N/cm^2) at the time when the dual-orifice nozzles were tested. The minimum inlet-air temperature obtainable was 65° F (292 K). The reference Mach number was varied from 0.075 to 0.10 for these tests. Relights were attempted at fuel-air ratios of 0.005 to 0.025 with the dual-orifice fuel nozzles but only at a fuel-air ratio of 0.01 for the simplex fuel nozzles. Burst tests were performed starting at a 0.01-fuel-air-ratio condition. The burst tests increased the fuel-air ratio to about 0.014 to determine if the combustor would respond with an increase in exit temperature.

Figure 16 compares the relight and blowout characteristics of the simplex and dual-orifice fuel nozzles with ambient and heated fuel. With ambient-temperature fuel, similar performance was observed with both types of fuel nozzles as evidenced in figure 16(a).

The relight performance was improved by the use of heated fuel. Figure 16(b) shows that at about 75° F (298 K) inlet-air total temperature, the combustor can be lit at a pressure 4.0 psi (2.8 N/cm^2) lower with fuel heated to about 275° F (409 K) than with ambient-temperature fuel. The blowout pressure was lowered 1.66 psi (1.15 N/cm^2) at that inlet-air temperature when 275° F (409 K) heated fuel was used. Also shown is a 1.5-psi (1.0 N/cm^2) improvement in relight performance at an inlet-air temperature of 290° F (417 K). Though not shown in figure 16(b), the simplex nozzles appear to have a similar improvement in relight performance as the dual-orifice nozzles with heated fuel.

Combustor response to rapid increase in fuel flow. - Fast-response thermocouple data were taken to see how well the combustor would react to a rapid increase in fuel-air ratio. For these tests a 0.005-inch- (0.127-mm-) diameter platinum/platinum-plus-13-percent-rhodium-wire thermocouple was mounted in the combustor exhaust plane. A thermocouple that had a measured time constant of 0.0333 second was used for the simplex nozzle tests, while for the dual-orifice nozzle test a thermocouple with a time constant of 0.0412 second was used. The test conditions were 30-psia (20.7 N/cm^2) combustor inlet total pressure, 150-foot-per-second (45.7-m/sec) reference velocity, and 600° F (589 K) inlet-air total temperature. The tests were conducted by first operating the combustor at a low fuel-air ratio. Then the fuel flow was rapidly increased to simulate a step change in fuel flow.

The results of these tests, shown in figures 17(a) and (b), are presented in terms of the ratios of instantaneous temperature rise over initial temperature rise. The "ideal" curve on these figures represents the ratio of temperature rise to initial temperature rise determined from steady-state data. To determine this curve the fast-response thermocouple was placed in the exhaust stream at the same location as in the fast-response tests. Then the fuel flow was increased from the initial value in small steps.

The fast-response thermocouple was then read after a steady-state condition was obtained at each fuel flow step.

As can be seen in figures 17(a) and (b) with a rapid increase in fuel flow, there is no significant lag in fuel-temperature response with either type of fuel nozzle. These figures are representative of inlet-air temperatures down to 250° F (395 K). The actual temperature response, being faster than the "ideal" response in figure 17(a), is thought to be due to inertial effects of the pintle in the dual-orifice nozzle. Since simplex nozzles have no moving parts that could overreact to a pressure change for a transient period, the temperature response followed the fuel response as would be expected. This dual-orifice nozzle transient condition could increase pattern factors considerably; but since it is short transient of about 1.6 seconds, this should present no serious durability problems.

Flame radiation. - Total flame radiation data were obtained at a single point in the combustor primary zone using a Leeds and Northrup Rayotube. The Rayotube was located in a spare ignition hole about 2.5 inches (6.4 cm) directly downstream of a fuel nozzle. Data presented in figure 18 were obtained with both simplex and dual-orifice fuel nozzles and represent three different airflow conditions with each nozzle type. As can be seen, the radiation heat flux is affected most by inlet-air temperature. This is to be expected as radiation is a function of temperature to the fourth power. Thus at any given fuel-air ratio the radiation would increase as inlet-air temperature increases. Since the heat flux is not increasing with increasing fuel-air ratio at any one inlet-air temperature and the combustion efficiency is known to be 100 percent over the entire fuel-air-ratio range of these conditions, it must be assumed the flame front is translating axially along the combustor and thus away from the fixed Rayotube position. If the flame front were stationary and a condition of 100 percent combustion efficiency exists, the heat flux will increase with increasing fuel-air ratio as higher flame temperatures are created. Reference 5 goes into greater explanation of heat flux behavior, including exceptions to the general statements noted here.

Figure 18 shows that simplex and dual-orifice fuel nozzles produced approximately the same heat flux at similar operating conditions except at 1150° F (895 K) inlet-air temperature. At this condition the dual-orifice nozzles produced heat fluxes considerably greater than simplex nozzles. Perhaps the flame front translated axially along the combustor at this condition with either the simplex or dual-orifice nozzles.

Smoke. - A von Brand Smokemeter and Walsh Densichron and Reflection Unit (3832A) were used to obtain smoke data. A Welsh Gray Scale (cat. no. 3827T) was used as a calibration reference. A combustor exhaust gas sample flow rate of 0.3 standard cubic foot per minute per square inch of filter paper ($2.19 \times 10^{-5} \text{ m}^3/\text{sec-cm}^2$) was maintained with a 2-psi (1.38 N/cm^2)-above-atmospheric pressure above the moving filter-paper tape and a 5-inches-of-mercury vacuum (8.5 N/cm^2) below the filter-paper tape. Clean filter-paper readings were taken for reference.

It was found that there was no significant difference in smoke emission between simplex and dual-orifice fuel nozzles. The measured values of smoke emission were about 20, the value of lightly visible smoke (ref. 6) at conditions of 90-psia (62.0-N/cm^2) inlet-air total pressure. At lower pressures, recorded values of smoke emission indicate that the smoke would be invisible.

SUMMARY OF RESULTS

A series of tests were performed to compare simplex and dual-orifice fuel nozzles with ambient and heated (300° F , 415 K) fuel in a jet engine combustor. The following results were obtained:

1. Combustion efficiency:

a. Both types of fuel nozzles performed at 100 percent combustion efficiency at inlet-air total temperatures of 600° to 1150° F (589 to 895 K), inlet total pressures of 60 to 90 psia (41.4 to 62.0 N/cm^2), and reference velocities of 100 to 150 feet per second (30.5 to 45.7 m/sec).

b. Both types of fuel nozzles showed similar trends of combustion efficiency as fuel temperature was increased, though with heated fuel the simplex nozzles gave a combustion efficiency slightly higher than the dual-orifice nozzles.

c. In general, heat addition to the fuel raises combustion efficiency.

2. Exit-temperature profile:

a. Both types of fuel nozzles produced similar pattern factors and exit-temperature profiles at simulated takeoff, Mach 2.7 cruise, and Mach 3.0 cruise conditions.

b. Operation of dual-orifice nozzles near the "knee" in their flow differential pressure curve can result in high pattern factors.

c. Heated fuel improved pattern factor at ambient-temperature (65° F , 292 K) and pressure conditions, but increased pattern factor at ambient pressure and 590° F (584 K) inlet-air temperature.

d. Pattern factors of both types of nozzles decreased (improved) with increasing inlet-air temperature.

3. Blowout and relight performance:

a. With ambient-temperature fuel, both types of fuel nozzles performed similarly.

b. The inlet-air total pressure necessary to ignite the combustor at 75° F (298 K) was lowered by 4.0 psi (2.8 N/cm^2) when heated fuel was used. Combustor pressure at blowout was reduced 1.66 psi (1.15 N/cm^2) at 75° F (298 K) with heated fuel.

4. Both types of fuel nozzles demonstrated very good exhaust temperature response to rapid increases in fuel flow.

5. Flame radiation at a fixed location:

a. Both types of fuel nozzles produced similar levels of flame radiation at moderate inlet-air temperatures (600° F, 589 K).

b. Dual-orifice nozzles produced much higher levels of radiation at high inlet-air temperatures (1150° F, 894 K).

6. Both types of fuel nozzles produced lightly visible smoke (smoke number, 20) at 90.0-psia (62-N/cm^2) inlet-air total pressure and no visible smoke at lower pressures.

7. Fuel nozzle durability:

a. Simplex nozzles were the most trouble free of the two nozzle types.

b. Dual-orifice nozzles perform satisfactorily but more care was taken to assure that fouling and sticking of the moving parts was minimized.

Lewis Research Center,

National Aeronautics and Space Administration,

Cleveland, Ohio, February 9, 1971,

720-03.

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TABLE I. - FUEL NOZZLE FLOW RANGES

Fuel nozzle type	Total fuel flow range for 24 fuel nozzles, lb/hr (kg/sec)	
	Minimum	Maximum
Number 1 simplex	3100 (0.39)	10 000 (1.26)
Number 2 simplex	1800 (0.23)	6 500 (0.82)
Number 3 simplex	450 (0.06)	1 850 (0.23)
Dual orifice	575 (0.07)	20 000 (2.52)

TABLE II. - TEST DATA

(a) Number 1 simplex nozzle

Run	Inlet-air conditions						Combustor operating conditions										Combustor performance characteristics									
	Total pressure		Total temperature		Airflow		Diffuser inlet Mach number	Reference velocity		Fuel-air ratio	Average outlet temperature		Inlet fuel temperature		Fuel nozzle differential pressure		Pattern factor	Combustor average temperature rise		Combustor pressure loss, percent	Combustion efficiency, percent	Enthalpy		Flame radiation heat flux		
																										lb/sec
	psia	N/cm ²	°F	K	ft/sec	m/sec		°F	K		°F	K	psid	N/cm ²	°F	K		Btu/lb	J/kg			Btu/(ft ²)(hr)	W/cm ²			
205	29.6	20.4	91	306	105.4	47.8	0.657	146	44.5	0.0138	496	531	65	291	131	90	0.532	404	225	20.98	41.5	---	---	-----	----	
206	29.6	20.4	89	305	105.7	48.0	.657	146	44.3	.0119	580	578	67	293	97	67	.441	491	273	20.97	57.7	---	---	-----	----	
207	29.8	20.5	594	585	58.9	26.7	.440	158	48.1	.0142	1499	1088	87	304	44	30	.267	905	503	11.18	97.5	---	---	-----	----	
208	29.8	20.6	595	586	58.8	26.7	.439	158	48.0	.0210	1907	1315	85	303	94	65	.285	1312	729	11.61	99.0	---	---	-----	----	
209	29.9	20.6	409	483	69.7	31.6	.516	153	46.6	.0163	1430	1050	83	302	79	55	.319	1020	567	13.3	94.2	---	---	-----	----	
210	29.6	20.4	401	478	69.8	31.7	.484	153	46.7	.0248	1979	1355	80	300	188	130	.335	1577	876	13.9	100.1	---	---	-----	----	
212	29.6	20.4	310	428	77.9	35.4	.522	152	46.4	.0213	1576	1131	76	297	174	120	.457	1266	704	15.4	90.8	---	---	-----	----	
213	29.5	20.4	307	426	77.8	35.3	.522	152	46.3	.0250	1838	1276	75	297	240	166	.363	1531	851	15.9	95.3	---	---	-----	----	
214	29.8	20.6	262	401	82.5	37.4	.539	150	45.7	.0221	1468	1070	75	297	209	144	.559	1206	670	16.4	83.2	---	---	-----	----	
591	90.5	62.4	608	593	111.1	50.4	.253	100.1	30.5	-----	-----	-----	--	---	---	---	-----	0	0	3.71	-----	---	---	2.5×10 ³	0.8	
592	90.6	62.5	604	591	111.6	50.6	.253	100.2	30.5	.0133	1504	1091	66	292	144	99	.366	900	500	3.76	102.5	---	---	-----	----	
593	90.5	62.4	606	592	111.8	50.7	.254	100.7	30.7	.0158	1664	1180	66	292	204	141	.401	1058	588	3.87	102.9	---	---	47.0	14.8	
594	90.5	62.4	605	592	111.8	50.7	.254	100.7	30.7	.0182	1812	1262	65	291	272	188	.390	1207	671	3.91	103.1	---	---	52.0	16.4	
595	60.5	41.7	1060	844	64.9	29.4	.267	124.6	38.0	.0163	2057	1398	73	296	74	51	.248	997	554	4.28	100.0	---	---	62.5	19.7	
596	60.5	41.7	1050	839	72.5	32.9	.301	138.1	42.1	.0112	1755	1231	71	295	45	31	.226	705	392	5.19	100.4	---	---	-----	----	
597	60.4	41.7	1051	840	72.7	33.0	.303	138.8	42.3	.0139	1917	1320	71	295	68	47	.234	866	481	5.31	100.6	---	---	-----	----	
598	61.4	42.4	1048	838	77.2	35.0	.317	144.7	44.1	.0163	2056	1398	68	293	105	73	.255	1008	560	5.70	101.0	---	---	55.5	17.5	
599	61.7	42.5	1051	840	76.2	34.6	.312	142.6	43.4	.0178	2139	1444	70	294	121	83	.270	1088	604	5.57	100.9	---	---	-----	----	
600	60.1	41.5	1050	839	73.8	33.5	.309	141.5	43.1	.0183	2169	1460	68	293	121	84	.275	1118	621	5.53	100.8	---	---	-----	----	
601	90.2	62.2	1157	898	106.4	48.3	.308	145.5	44.4	.0098	1766	1236	73	296	72	50	.220	609	338	5.11	100.5	---	---	-----	----	
602	90.3	62.3	1151	895	106.0	48.1	.306	144.4	44.0	.0133	1977	1354	71	295	132	91	.225	826	459	5.18	101.4	---	---	-----	----	
603	90.9	62.7	1148	893	106.7	48.4	.306	144.2	43.9	.0158	2115	1430	68	293	187	129	.247	967	537	5.33	101.4	---	---	114.0	35.9	
604	90.5	62.4	1150	894	106.8	48.4	.308	145.0	44.2	-----	-----	-----	--	---	---	---	-----	0	0	5.13	-----	---	---	10.6	3.3	
617	40.8	28.1	597	587	75.9	34.4	.414	149.2	45.5	.0218	1993	1363	67	293	189	130	.174	1396	776	8.87	102.6	---	---	-----	----	
618	30.6	21.1	605	592	56.9	25.8	.418	150.2	45.8	.0218	1981	1356	70	294	105	72	.168	1376	764	9.50	101.3	---	---	-----	----	
626	58.7	40.5	1052	840	77.5	35.2	.336	152.8	46.6	.0126	1810	1261	75	297	70	48	.211	758	421	4.96	97.9	---	---	52.6×10 ³	16.6	
627	59.9	41.3	1051	839	80.2	36.4	.342	154.8	47.2	.0148	1962	1346	74	297	101	70	.185	911	506	6.79	101.5	---	---	49.6	15.6	
628	59.9	41.3	1051	839	76.7	34.8	.327	148.0	45.1	.0191	2154	1452	76	298	154	106	.225	1103	613	6.08	96.8	---	---	44.7	14.1	
629	59.2	40.8	1052	840	78.6	35.7	.338	153.7	46.8	.0206	2273	1518	75	297	187	129	.218	1221	678	5.59	100.0	---	---	42.3	13.3	
638	59.3	40.8	597	587	115.5	52.4	.428	156.5	47.7	.0217	1987	1359	71	295	441	304	.379	1390	772	9.68	102.7	---	---	-----	----	
639	49.8	34.3	600	589	96.6	43.9	.423	156.8	47.8	.0214	1992	1362	71	295	301	207	.299	1392	773	9.28	104.1	---	---	-----	----	
640	39.5	27.2	603	591	79.1	35.9	.443	162.0	49.4	.0208	1949	1338	73	296	190	131	.351	1346	748	9.86	103.1	---	---	-----	----	
643	30.2	20.8	597	587	57.2	26.0	.422	152.2	46.4	.0217	1893	1252	68	293	106	73	.318	1306	726	9.46	95.8	---	---	-----	----	
645	14.8	10.2	614	597	27.2	12.3	.406	150.7	45.9	.0202	1661	1178	71	295	22	15	.306	1047	582	4.93	82.6	---	---	-----	----	
646	14.3	9.8	610	594	30.1	13.7	.464	172.2	52.5	.0205	1781	1245	69	294	27	19	.284	1171	651	5.17	91.0	---	---	-----	----	
656	59.5	41.0	1056	842	76.4	34.6	.327	148.8	45.4	.0129	1851	1284	73	296	67	46	.175	795	417	6.20	100.5	---	---	54.8	17.3	
657	59.8	41.2	1058	843	77.8	35.3	.331	151.3	46.1	.0156	1999	1366	73	296	101	70	.195	941	523	6.44	99.9	---	---	54.5	17.2	
658	59.0	40.6	1058	843	76.0	34.5	.328	149.7	45.6	.0192	2175	1464	71	295	145	100	.217	1117	621	5.16	97.6	---	---	48.8	15.4	
659	60.1	41.4	1057	843	76.0	34.5	.319	146.9	44.8	.0207	2263	1513	74	297	169	116	.224	1206	670	6.89	98.4	---	---	43.0	13.6	
660	59.2	40.8	1056	842	76.7	34.8	.328	150.4	45.8	.0202	2258	1510	74	297	163	112	.224	1202	668	5.57	100.3	---	---	43.8	13.8	

TABLE II. - Continued. TEST DATA

(b) Number 2 simplex nozzle

Run	Inlet-air conditions						Combustor operating conditions										Combustor Performance characteristics							
	Total pressure		Total temperature		Airflow		Diffuser inlet Mach number	Reference velocity		Fuel-air ratio	Average outlet temperature		Inlet fuel temperature		Fuel nozzle differential pressure		Pattern factor	Combustor average temperature rise	Combustor pressure loss, percent	Combustion efficiency, percent	Enthalpy		Flame radiation	
	psia	N/cm ²	°F	K	lb/sec	kg/sec		ft/sec	m/sec		°F	K	°F	K	psid	N/cm ²					Btu/lb	J/kg	Btu/(ft ²)(hr)	W/cm ²
40	30.6	21.1	595	586	56.7	25.7	0.404	148.8	45.4	0.0215	1963	1346	75	297	332	229	0.361	1368	760	10.70	102.0	-----	-----	
42	25.2	17.4	593	585	47.3	21.5	.411	150.2	45.8	.0216	1957	1343	81	301	233	160	.344	1364	758	10.52	101.3	-----	-----	
44	20.1	13.8	591	584	38.2	17.3	.414	152.0	46.3	.0215	1943	1335	81	301	148	102	.279	1352	751	9.83	100.8	-----	-----	
46	15.0	10.3	583	578	28.1	12.8	.406	149.0	45.4	.0216	1914	1319	86	303	83	57	.260	1331	739	8.89	98.4	-----	-----	
556	18.0	12.4	64	291	26.3	11.9	.203	58.7	17.9	.0079	286	414	47	282	73	50	.333	223	124	2.62	38.0	-----	-----	
558	17.8	12.2	63	290	26.5	12.0	.208	59.8	18.2	.0098	376	464	49	283	12	8	.360	313	174	2.65	43.5	-----	-----	
559	17.7	12.2	65	292	26.5	12.0	.209	60.3	18.4	.0126	522	546	49	283	21	14	.447	457	254	2.69	50.5	-----	-----	
560	17.8	12.3	63	290	26.6	12.0	.208	59.9	18.3	.0157	755	675	50	283	34	23	.532	692	385	2.83	62.8	-----	-----	
561	17.7	12.2	61	289	26.6	12.1	.208	60.0	18.3	.0193	1114	874	52	284	55	38	.427	1053	585	3.15	79.5	-----	-----	
562	18.0	12.4	62	290	26.5	12.0	.205	59.1	18.0	.0236	1544	1113	53	285	84	58	.351	1482	823	3.08	93.8	-----	-----	
563	17.7	12.2	55	286	26.3	11.9	.205	58.9	18.0	.0277	1857	1287	53	285	118	81	.293	1802	1001	3.05	99.2	-----	-----	
564	17.8	12.2	54	285	26.4	12.0	.204	58.5	17.8	.0238	1633	1163	290	416	114	79	.310	1579	877	3.20	98.7	-----	-----	
565	17.7	12.2	55	286	26.4		.206	58.9	17.9	.0195	1332	995	282	412	75	52	.359	1277	709	3.27	94.6	-----	-----	
566	17.8	12.3	55	286	26.5		.206	58.9	18.0	.0269	1857	1287	302	423	154	106	.369	1802	1001	3.22	101.0	-----	-----	
567	17.6	12.2	54	285	26.4		.206	59.0	18.0	.0169	1113	874	283	412	55	38	.383	1059	589	3.07	89.4	-----	-----	
568	17.6	12.1	54	285	26.5		.207	59.3	18.1	.0133	806	703	270	406	33	23	.441	752	418	2.88	78.5	-----	-----	
569	17.6	12.1	54	285	26.5		.207	59.3	18.1	.0099	526	548	280	411	18	12	.383	472	262	2.75	64.6	-----	-----	
570	17.7	12.2	52	284	26.4		.204	58.5	17.8	.0080	394	474	245	392	12	8	.344	342	190	2.67	57.3	-----	-----	
571	17.9	12.3	599	588	26.2	11.9	.302	118.4	36.1	.0078	1079	855	59	288	10	7	.266	480	267	5.46	90.1	-----	-----	
572	17.8	12.3	603	590	26.2		.304	119.6	36.4	.0100	1224	935	57	287	15	10	.293	621	345	5.54	92.8	-----	-----	
573	17.9	12.3	607	593	26.3		.305	120.0	36.6	.0139	1495	1086	62	290	31	21	.305	888	493	5.76	97.3	-----	-----	
574	17.9	12.4	607	593	26.2		.303	119.2	36.3	.0179	1745	1225	60	289	51	35	.284	1138	632	5.84	98.7	-----	-----	
575	17.8	12.3	606	592	26.3		.306	120.5	36.7	.0218	1967	1348	60	289	77	53	.283	1361	756	6.00	99.1	-----	-----	
576	17.8	12.2	606	592			.306	120.8	36.8	.0179	1764	1235	284	413	66	45	.317	1158	643	5.84	100.1	-----	-----	
577	17.6	12.1	603	591			.308	121.3	37.0	.0140	1527	1104	280	411	39	27	.288	924	513	5.88	100.2	-----	-----	
578	17.8	12.3	605	592			.305	120.3	36.7	.0213	1957	1342	300	422	96	66	.326	1352	751	5.96	99.8	-----	-----	
579	17.5	12.1	603	590			.310	121.9	37.2	.0099	1266	959	285	414	20	14	.259	663	368	5.85	98.9	-----	-----	
580	17.7	12.2	606	592	26.2		.306	120.7	36.8	.0077	1120	877	263	402	11	7	.251	514	286	5.64	96.9	-----	-----	
581	17.6	12.2	603	590	26.2		.306	120.6	36.8	-----	-----	-----	-----	-----	-----	-----	0	0	5.40	-----	-----	-----		
582	90.5	62.4	603	590	107.8	48.9	.243	96.8	29.5	.0138	1527	1104	72	295	586	404	.310	924	513	3.33	102.0	-----	-----	
583	90.6	62.4	612	596	110.7	50.2	.252	100.2	30.5	.0159	1669	1183	70	295	848	585	.323	1057	587	3.81	102.2	49.5	115.1	
584	60.2	41.5	1052	840	73.6	33.4	.309	141.1	43.0	.0111	1747	1226	78	299	181	125	.249	696	387	5.35	100.1	-----	-----	
585	60.0	41.4	1054	841	73.2	33.2	.308	141.0	43.0	.0139	1910	1316	76	298	281	194	.263	856	476	5.31	100.0	-----	-----	
586	60.2	41.5	1057	843	73.0	33.1	.306	140.4	42.8	.0185	2178	1465	74	297	515	355	.304	1121	623	5.42	100.1	66.5	154.6	
588	90.8	62.6	1150	894	110.4	50.1	.319	149.3	45.5	.0094	1740	1220	78	299	308	212	.262	590	328	5.50	100.6	124.0	288.3	
589	90.5	62.4	1159	899	110.5	50.1	.321	150.9	46.0	.0128	1948	1337	76	297	577	398	.249	788	438	5.56	100.9	-----	-----	
590	90.5	62.4	1161	901	110.2	50.0	.321	150.8	46.0	.0152	2095	1419	77	298	830	572	.253	934	519	5.67	101.4	122.0	283.7	
708	14.8	10.2	592	584	26.9	12.2	.393	145.7	44.4	.0229	1968	1349	58	288	90	62	.270	1376	764	9.67	96.9	-----	-----	
709	10.4	7.2	591	584	18.4	8.3	.380	142.1	43.3	.0222	1849	1283	61	289	39	27	.271	1258	699	7.44	91.0	-----	-----	
716	40.4	27.8	602	590	73.8	33.5	.397	147.7	45.0	.0226	2016	1376	71	295	736	508	.360	1426	792	9.73	100.8	-----	-----	
721	10.1	7.0	592	584	18.9	8.6	.408	149.8	45.7	.0220	1883	1302	68	293	43	30	.281	1291	717	9.40	94.3	-----	-----	
717	30.6	21.1	603	590	55.1	25.0	.392	146	44.5	.0225	1993	1363	69	294	394	272	.353	1390	773	10.17	99.4	-----	-----	
718	25.6	17.7	598	588	45.0	20.4	.381	142	43.3	.0229	2005	1369	69	294	268	185	.315	1407	780	9.61	98.9	-----	-----	
719	20.5	14.1	597	587	36.8	16.7	.389	145	44.2	.0226	2186	1470	68	293	174	120	.262	1589	883	9.52	98.3	-----	-----	
720	14.8	10.2	592	584	26.9	12.2	.393	146	44.5	.0229	1968	1349	67	293	90	62	.270	1376	764	9.67	96.9	-----	-----	

TABLE II. - Continued. TEST DATA

(c) Number 3 simplex nozzle

Run	Inlet-air conditions							Combustor operating conditions									Combustor performance characteristics							
	Total pressure		Total temperature		Airflow		Diffuser inlet Mach number	Reference velocity		Fuel-air ratio	Average outlet temperature		Inlet fuel temperature		Fuel nozzle differential pressure		Pattern factor	Combustor average temperature rise		Combustor pressure loss, percent	Combustion efficiency, percent	Enthalpy		
																								lb/sec
	psia	N/cm ²	°F	K	lb/sec	kg/sec		ft/sec	m/sec		°F	K	psid	N/cm ²	°F	K		Btu/lb	J/kg					
49	15.6	10.7	596	587	28.9	13.1	0.415	148.1	45.1	0.0183	1719	1211	74	297	919	633	0.205	1123	624	11.16	96.7	-----	-----	
57	8.3	5.7	579	577	15.6	7.1	.420	147.4	44.9	.0218	1837	1276	73	296	354	244	.215	1258	699	10.80	92.3	-----	-----	
68	10.4	7.2	584	580	19.2	8.7	.409	145.3	44.3	.0216	1857	1287	60	289	539	372	.214	1277	709	10.56	94.1	-----	-----	
74	5.3	3.7	559	566	10.2	4.6	.425	148.4	45.2	.0221	1776	1242	61	289	142	98	.241	683	379	6.38	87.9	-----	-----	
289	17.9	12.4	587	581	26.7	12.1	.310	118.9	36.3	.0103	1274	963	289	416	306	211	.253	687	382	5.78	99.1	-----	-----	
291	17.9	12.3	587		26.7		.311	119.2	36.3	.0084	1148	893	293	418	202	139	.236	561	312	5.82	97.7	-----	-----	
292	18.1	12.5	586		26.6		.306	117.5	35.8	.0105	1262	957	91	306	245	169	.238	676	376	5.72	96.3	-----	-----	
293	17.9	12.3	597		26.6		.310	118.8	36.2	.0085	1120	878	86	303	154	106	.240	534	296	5.84	93.0	-----	-----	
294	17.8		111	317	26.4	12.0	.219	64.7	19.7	.0106	629	605	72	213	195	135	.347	517	287	3.06	67.6	-----	-----	
295	17.8		107	315	26.5	12.0	.219	64.5	19.7	.0086	439	500	71	295	119	82	.368	332	184	3.00	52.7	-----	-----	
296	17.8		97	309	26.4	12.0	.217	63.3	19.3	.0086	606	592	281	411	186	128	.340	509	283	3.05	80.4	-----	-----	
298	18.1	12.5	94	307	26.3	11.9	.211	61.7	18.8	.0105	776	686	294	419	288	199	.350	682	379	2.94	89.4	-----	-----	

TABLE II. - Continued. TEST DATA

(d) Dual-orifice fuel nozzles

Run	Inlet-air conditions						Combustor operating conditions										Combustor performance characteristics								
	Total pressure		Total temperature		Airflow		Diffuser inlet Mach number	Reference velocity		Fuel-air ratio	Average outlet temperature		Inlet fuel temperature		Fuel nozzle differential pressure		Pattern factor	Combustor average temperature rise		Combustor pressure loss, percent	Combustion efficiency, percent	Enthalpy		Flame radiation heat flux	
	psia	N/cm ²	°F	K	lb/sec	kg/sec		ft/sec	m/sec		°F	K	psid	N/cm ²	°F	K		Btu/lb	J/kg			Btu/(ft ²)(hr)	W/cm ²		
215	29.9	20.6	75	297	107.3	48.7	0.660	142.4	43.4	0.0120	407	482	80	300	147	101	0.513	332	185	21.45	38.4	----	----	-----	----
216	29.9	20.6	72	295	107.4	48.7	.660	141.8	43.2	.0129	385	469			150	103	.502	313	174	22.10	34.1	----	----	-----	----
217	29.9	20.6	245	391	82.3	37.3	.521	145.7	44.4	.0121	935	775			138	95	.349	690	383	14.85	81.3	----	----	-----	----
218	30.0	20.7	254	396	82.1	37.2	.524	147.0	44.8	.0191	1267	959			154	106	.531	1013	563	15.61	79.4	----	----	-----	----
219	29.9	20.6	271	406	80.5	36.5	.523	148.1	45.1	.0230	1533	1107			164	113	.479	1262	701	16.20	84.1	----	----	-----	----
220	30.0	20.7	352	451	74.0	33.6	.501	150.9	46.0	.0118	1052	840			134	92	.289	700	389	14.36	86.1	----	----	-----	----
222	30.2	20.8	352	451	72.8	33.0	.483	147.8	45.1	.0241	1822	1268			162	111	.363	1470	817	14.36	95.0	----	----	-----	----
223	30.1	20.8	442	501	67.0	30.4	.463	151.6	46.2	.0113	1152	896			130	89	.336	710	395	12.32	92.1	----	----	-----	----
225	29.7	20.5	455	508	65.3	29.6	.461	152.1	46.3	.0245	1968	1349	86	303	157	108	.329	1513	840	13.10	97.8	----	----	-----	----
226	30.3	20.9	593	585	58.5	26.5	.429	154.0	46.9	.0113	1308	982	89	305	127	87	.379	715	397	11.05	95.3	----	----	-----	----
228	30.1	20.7	611	595	57.4	26.0	.428	154.8	47.2	.0218	1940	1333	92	306	146	100	.292	1330	739	11.54	97.1	----	----	-----	----
232	59.5	41.0	593	585	111.7	50.6	.411	150.1	45.8	.0116	1363	1013	93	307	147	101	.263	770	428	9.69	99.4	----	----	-----	----
234	59.5	41.0	597	587	112.1	50.9	.415	151.3	46.1	.0219	1980	1355	95	308	187	129	.313	1382	768	10.17	100.3	----	----	-----	----
235	50.0	34.5	597	587	95.1	43.1	.418	152.4	46.5	.0115	1351	1006	96	309	141	97	.274	755	419	9.84	98.7	----	----	-----	----
237	49.6	34.2	597	587	93.4	42.4	.414	151.0	46.0	.0222	1991	1362	95	308	173	119	.328	1394	774	10.31	99.9	----	----	-----	----
238	40.2	27.7	601	589	76.2	34.5	.419	152.7	46.5	.0115	1355	1008	97	309	134	92	.244	753	418	10.08	98.4	----	----	-----	----
240	39.7	27.4	595	586	75.3	34.2	.418	151.8	46.3	.0220	1976	1353	99	310	158	109	.314	1381	767	10.56	99.8	----	----	-----	----
243	25.3	17.4	588	582	47.3	21.4	.398	148.5	45.3	.0117	1330	994	88	304	123	85	.445	742	412	9.89	95.5	----	----	-----	----
245	24.8	17.1	595	586	47.6	21.6	.414	153.8	46.9	.0218	1936	1331	92	307	140	96	.310	1341	745	10.81	97.7	----	----	-----	----
248	20.1	13.9	594	585	38.5	17.5	.413	153.2	46.7	.0216	1903	1313	95	308	133	92	.261	1309	727	11.23	96.0	----	----	-----	----
249	15.2	10.5	594	585	29.4	13.3	.417	154.2	47.0	.0113	1273	962	96	309	116	80	.516	679	377	11.34	90.2	----	----	-----	----
251	15.1	10.4	592	584	30.3	13.7	.437	159.8	48.7	.0204	1812	1262	96	309	126	87	.400	1220	678	12.68	94.1	----	----	-----	----
485	17.7	12.2	69	294	25.8	11.7	.206	59.1	18.0	.0079	363	457	62	290	72	50	.406	293	163	2.77	49.6	----	----	-----	----
486	17.8	12.3	67	293	25.9	11.8	.206	58.8	17.9	.0101	490	528	62	290	116	80	.523	423	235	2.73	57.2	----	----	-----	----
487	17.7	12.2	66	292	25.9	11.7	.205	58.7	17.9	.0131	643	613	65	292	119	82	.756	577	321	2.83	61.4	----	----	-----	----
489	17.9	12.3	65	291	25.8		.203	58.0	17.7	.0151	778	688	66	292	119	82	.616	714	397	2.79	67.1	----	----	-----	----
490	17.7	12.2	63	290	25.8		.205	58.4	17.8	.0079	457	509	260	400	94	65	.464	394	219	2.74	66.3	----	----	-----	----
491	17.9	12.4	62	290	25.8		.202	57.6	17.5	.0102	611	595	270	405	113	78	.655	548	305	2.74	73.4	----	----	-----	----
492	17.9	12.4	64	291	25.8		.202	57.8	17.6	.0131	808	704	278	410	115	79	.568	744	413	2.73	78.9	----	----	-----	----
493	17.9	12.3	62	290	25.8		.201	57.7	17.6	.0150	951	784	279	411	117	81	.639	889	494	3.06	83.5	----	----	-----	----
494	17.7	12.2	593	585	25.7		.300	117.2	35.7	.0080	1100	867	278	410	110	76	.411	507	282	5.77	92.8	----	----	-----	----
495	17.7	12.2	587	581	25.8		.298	116.2	35.4	.0101	1237	943	261	400	108	74	.712	651	362	5.78	94.9	----	----	-----	----
496	17.7	12.2	590	583	25.8		.301	117.2	35.7	.0131	1423	1046	286	414	109	75	.564	833	463	5.95	95.6	----	----	-----	----
497	17.8	12.3	594	585	25.7		.299	116.5	35.5	.0152	1560	1122	289	416	110	76	.499	966	537	5.91	96.7	----	----	-----	----
498	17.8	12.3	588	582	25.9	11.8	.301	116.6	35.5	.008	1065	847	85	303	103	71	.284	478	265	5.72	87.2	----	----	-----	----

TABLE II. - Concluded. TEST DATA

(d) Concluded. Dual-orifice fuel nozzles

Run	Inlet-air conditions						Combustor operating conditions										Combustor performance characteristics								
	Total pressure		Total temperature		Airflow		Diffuser inlet Mach number	Reference velocity		Fuel-air ratio	Average outlet temperature		Inlet fuel temperature		Fuel nozzle differential pressure		Pattern factor	Combustor average temperature rise		Combustor pressure loss, percent	Combustion efficiency, percent	Enthalpy		Flame radiation heat flux	
					lb/sec	kg/sec																Btu/lb	J/kg		
	psia	N/cm ²	°F	K				ft/sec	m/sec															Btu/(ft ²)(hr)	W/cm ²
											°F	K	°F	K	psid	N/cm ²		°F	K						
499	17.7	12.2	590	583	25.8	11.7	0.300	116.9	35.6	0.0101	1214	930	78	299	112	77	0.646	624	347	5.70	91.5	-----	-----	-----	---
500	17.7	12.2	592	584	25.8	11.7	.302	117.2	35.7	0.132	1413	1040	76	297	113	78	.509	820	456	5.88	94.1	-----	-----	-----	---
501	17.8	12.3	598	588	25.7	11.7	.300	117.0	35.7	0.152	1544	1113	77	298	114	79	.341	946	526	5.96	95.3	-----	-----	-----	---
502	24.8	17.1	318	432	52.1	23.7	.387	124.2	37.9	.0086	804	702	111	317	117	81	.479	486	270	8.74	79.6	-----	-----	-----	---
503	25.0	17.2	304	424	43.9	19.9	.310	102.5	31.2	.0084	776	687	84	302	115	79	.416	472	263	5.96	79.1	-----	-----	-----	---
504	19.8	13.7	299	421	44.0	20.0	.408	127.8	39.0	.0084	747	670	77	298	115	79	.417	448	249	9.77	75.0	-----	-----	-----	---
505	19.7	13.6	59	288	66.7	30.3	.572	131.5	40.1	.0091	394	474	60	289	125	86	.460	334	186	17.66	50.0	0	0	-----	---
506	19.8		61	289	66.5	30.2	.570	131.4	40.1	.0101	420	489	59	288	127	88	.411	359	199	17.61	48.8	-----	-----	-----	---
507	19.8		59	288	66.6	30.2	.567	131.2	40.0	.0130	412	484	62	290	133	92	.413	353	196	17.40	38.0	-----	-----	-----	---
508	19.7		62	290	66.6	30.2	.573	132.1	40.3	.0162	284	413	63	290	139	96	.596	222	124	17.76	19.7	0	0	-----	---
509	19.8		60	288	67.2	30.5	.576	132.0	40.2	.0090	416	487	292	418	122	84	.393	357	198	17.84	53.4	-----	-----	-----	---
510	19.8	13.7	56	287	67.1	30.4	.570	130.7	39.8	.0100	438	499	300	422	124	85	.385	382	212	17.66	51.8	-----	-----	-----	---
511	19.6	13.5	64	291	66.6	30.2	.583	133.4	40.7	.0132	374	463	300	422	131	90	.445	310	172	18.18	32.7	-----	-----	-----	---
512	19.7	13.6	67	292	66.6	30.2	.577	133.3	40.6	.0164	243	390	300	422	137	95	.805	176	98	17.52	15.3	-----	-----	-----	---
514	19.7	13.6	312	429	46.5	21.1	.447	137.9	42.0	.0079	720	656	67	293	115	80	.432	409	227	11.57	72.4	59.0	137.2	-----	---
515	19.7	13.6	305	425	44.8	20.3	.424	132.0	40.2	.0102	862	734	70	295	118	81	.507	557	310	10.67	77.6	-----	-----	-----	---
516	19.8	13.7	303	424	44.5	20.2	.416	130.1	39.7	0.133	1065	847	70	294	124	85	.441	762	423	10.49	83.3	-----	-----	-----	---
517	19.9	13.7	305	425	44.5		.415	129.9	39.6	.0165	1258	954	70	294	128	88	.400	954	530	10.73	85.4	59.0	137.2	-----	---
520	19.8	13.6	303	424	44.6		.419	130.6	39.8	.0164	1262	957	297	420	126	87	.400	960	533	10.88	85.8	-----	-----	-----	---
521		13.7	303		44.5		.417	129.9	39.6	0.132	1086	859	296	420	120	83	.401	783	435	10.58	85.4	-----	-----	-----	---
522		13.6	304		44.6		.419	130.5	39.8	.0102	903	757	290	416	114	79	.399	599	333	10.63	83.1	-----	-----	-----	---
523			303		44.5		.418	130.3	39.7	.0082	778	688	283	412	111	77	.447	475	264	10.41	80.1	-----	-----	-----	---
525	19.7		588	581	32.9	14.9	.352	133.4	40.7	.0079	1094	863	282	412	109	75	.586	506	281	7.56	92.8	-----	-----	-----	---
526	19.8		592	584	32.8	14.9	.351	133.1	40.6	.0100	1230	939	283	412	109	75	.492	638	355	7.72	94.3	-----	-----	-----	---
527	19.8	13.7	594	585	33.0	15.0	.352	133.5	40.7	.0130	1421	1045	292	417	113	78	.416	827	459	7.73	95.2	-----	-----	-----	---
528	19.8	13.7	595	586	32.9	14.9	.350	133.1	40.6	.0161	1606	1147	293	418	116	80	.313	1010	561	7.80	96.1	-----	-----	-----	---
531	19.7	13.6	593	585	32.9	14.9	.352	133.8	40.8	0.160	1586	1136	79	299	120	82	.422	992	551	7.81	95.3	129.2	300.4	-----	---
532	19.6	13.5	592	584	32.9	14.9	.354	134.4	41.0	0.131	1405	1036	78	299	115	80	.327	814	452	7.86	94.0	-----	-----	-----	---
533	19.8	13.6	594	586	33.0	15.0	.353	134.1	40.9	.0099	1207	926	75	297	113	78	.533	613	341	7.65	92.2	-----	-----	-----	---
534	19.8	13.6	592	585	32.9	14.9	.352	133.6	40.7	0.080	1086	859	76	298	112	77	.640	494	274	7.59	90.8	129.2	300.4	-----	---
718	90.7	62.6	599	588	110.3	50.0	.248	98.5	30.0	.0130	1485	1080	84	302	151	104	.317	886	492	3.47	103.2	-----	-----	61.5×10 ³	19.4
719	90.9	62.7	598	588	109.8	49.8	.247	97.8	29.8	.0161	1679	1188	81	300	162	112	.318	1081	600	3.52	103.4	-----	-----	48.5	15.3
720	90.5	62.4	595	586	110.1	49.9	.248	98.2	29.9	0.180	1796	1253	81	300	171	118	.336	1201	667	3.57	103.8	-----	-----	-----	---
721	90.8	62.6	597	587	110.2	50.0	.248	98.0	29.9	0.201	1920	1322	78	298	178	123	.346	1323	735	3.64	103.4	-----	-----	38.5×10 ³	12.1
722	90.6	62.5	593	585	110.1	50.0	.248	97.9	29.8	0.221	2034	1385	79	299	187	129	.396	1441	800	3.68	103.5	-----	-----	37.0	11.7
726	90.7	62.6	603	590	111.5	50.6	.252	99.8	30.4	.0179	1802	1257	81	300	170	117	.308	1200	666	3.72	104.5	-----	-----	50.0	15.8
727	90.6	62.5	604	591	111.9	50.7	.253	100.4	30.6	0.218	2035	1386	77	298	186	128	.339	1431	795	3.79	104.3	-----	-----	42.5	13.4
728	60.3	41.6	1057	843	75.9	34.4	.318	145.9	44.4	0.104	1720	1211	92	306	130	90	.243	663	368	5.47	101.4	-----	-----	106.5	33.6
729	60.2	41.5	1055	842	76.6	34.8	.322	147.2	44.9	0.131	1885	1303	89	305	137	94	.235	830	461	5.77	102.5	-----	-----	87.5	27.6
731	60.1	41.4	1055	842	76.4	34.7	.322	147.2	44.9	0.152	2010	1372	86	303	143	98	.262	955	531	5.64	102.5	-----	-----	72.0	22.7
732	60.3	41.6	1054	841	75.0	34.0	.314	143.8	43.8	0.174	2139	1449	87	304	147	101	.286	1084	602	5.49	102.5	-----	-----	63.5	20.0
733	60.9	42.0	1056	842	75.5	34.2	.312	143.6	43.8	0.182	2187	1470	85	302	149	103	.288	1131	628	5.37	102.6	-----	-----	59.0	18.6
734	90.5	62.4	1153	896	111.2	50.4	.322	151.4	46.1	0.092	1742	1223	89	305	136	94	.233	589	327	5.47	102.5	-----	-----	177.0	55.8
735	90.6	62.5	1154		111.3	50.5	.322	151.4	46.1	0.126	1947	1337	90	305	150	103	.220	793	441	5.65	102.5	-----	-----	181.0	57.1
736	90.5	62.4	1153		111.4	50.5	.323	151.6	46.2	.0156	2120	1433	86	303	161	111	.262	966	537	5.67	102.5	-----	-----	157.0	49.5
737	90.4	62.3	1153		110.4	50.1	.320	150.5	45.9	.0172	2212	1485	84	302	166	115	.277	1060	589	5.59	102.6	-----	-----	146.0	46.0
738	90.5	62.4	1152	895	111.5	50.6	.323	151.6	46.2	0.126	1939	1333	88	305	149	103	.225	788	438	5.70	101.8	-----	-----	174.0	54.9
274	10.0	6.9	573	574	19.4	8.8	.414	152.4	46.5	0.214	1849	1283	106	314	116	80	.289	1276	709	10.82	94.1	-----	-----	-----	---
741	60.3	41.6	1054	841	77.4	35.1	.324	148.4	45.2	0.129	1875	1297	89	305	135	93	.217	821	456	5.66	102.5	-----	-----	86.0×10 ³	27.1
744	90.9	62.7	595	586	112.0	50.8	.251	99.5	30.3	0.177	1800	1255	85	303	169	116	.352	1205	670	3.68	105.6	-----	-----	52.0	16.1

TABLE III. - SIMULATED ENGINE

OPERATING CONDITIONS

Condition	Inlet-air conditions				Combustor reference velocity	
	Total pressure		Total temperature			
	psia	N/cm ²	°F	K	ft/sec	m/sec
Takeoff	90.0	62.0	600	589	100.0	30.5
Mach 2.7 cruise	60.0	41.4	1050	839	140.0	42.6
Mach 3.0 cruise	90.0	62.0	1150	894	150.0	45.7

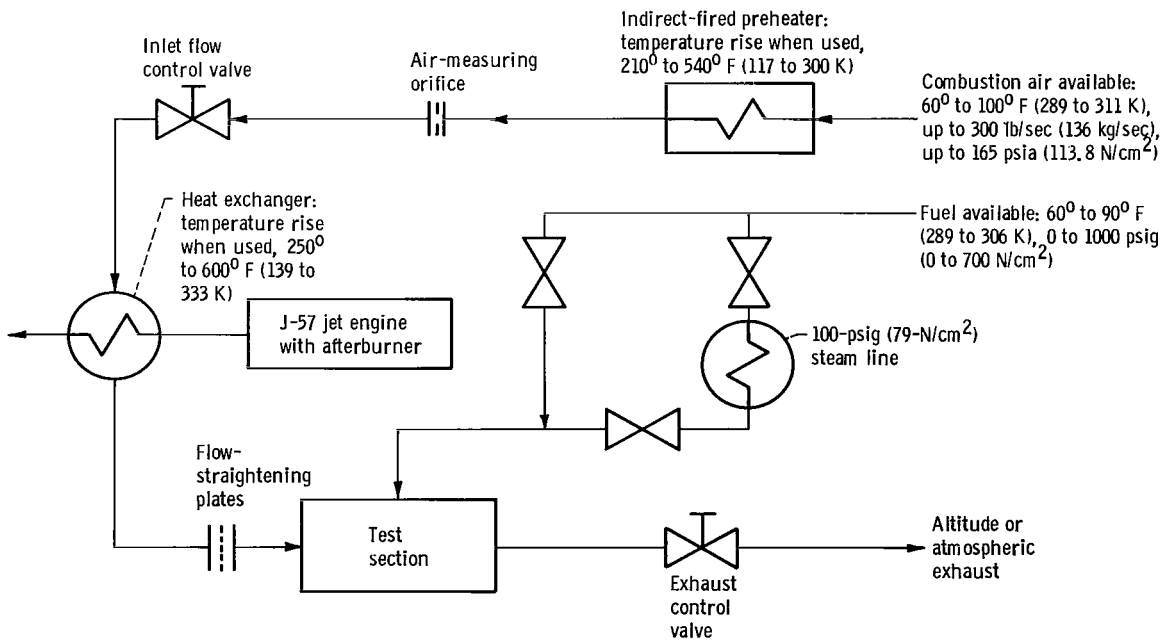


Figure 1. - Schematic of test facility combustion air and fuel.

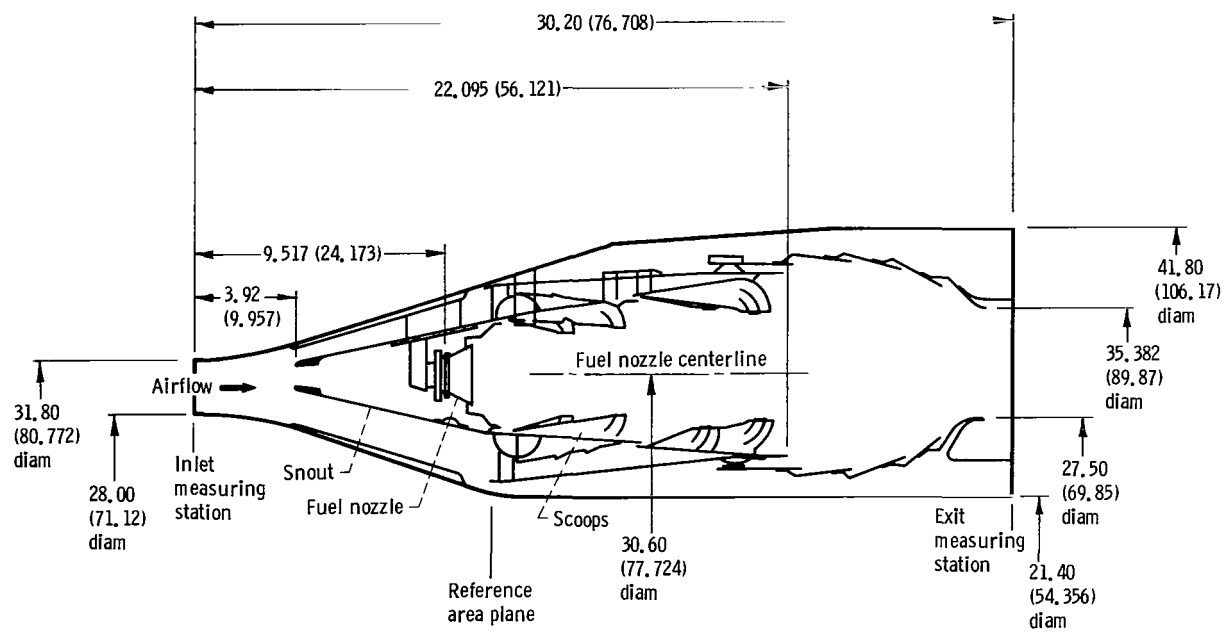


Figure 2. - Cross section of combustor. Dimensions are in inches (cm).

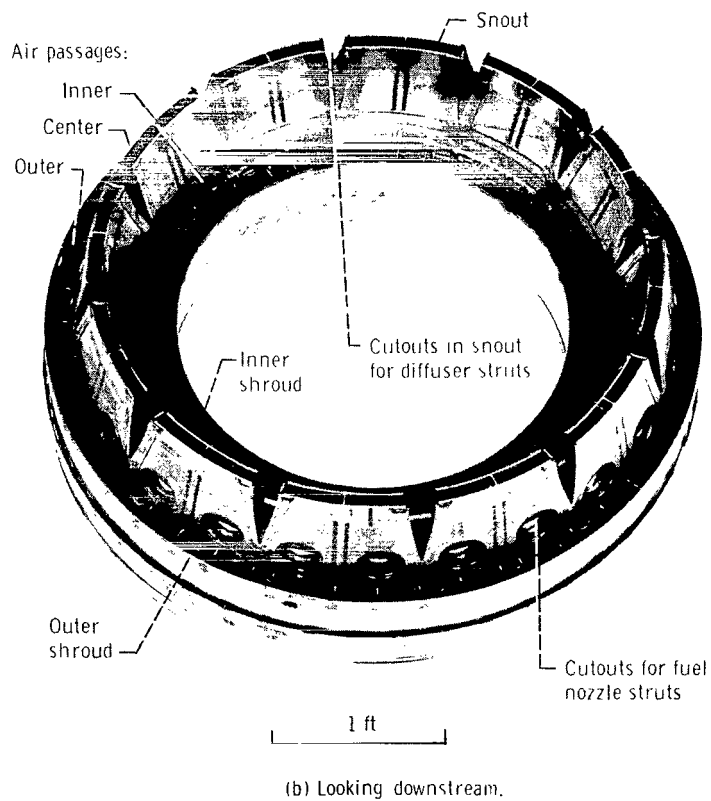
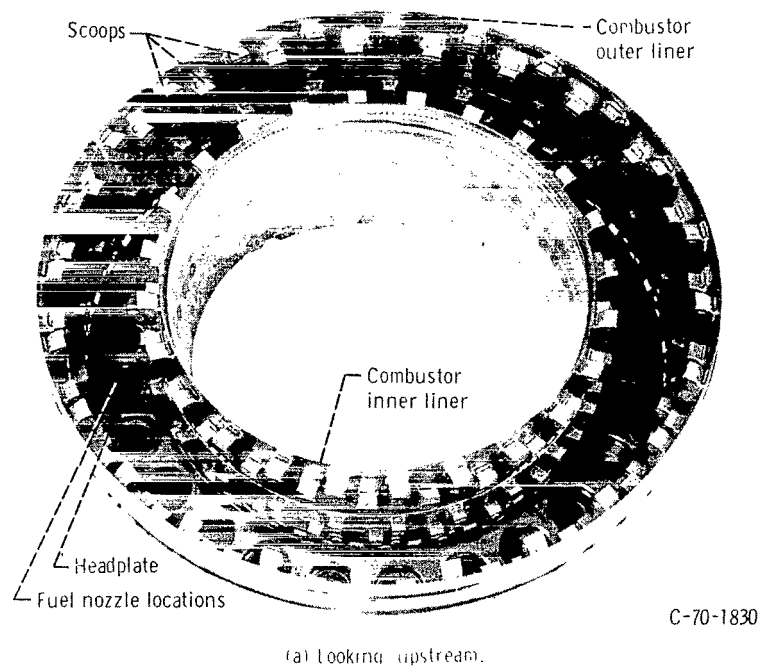
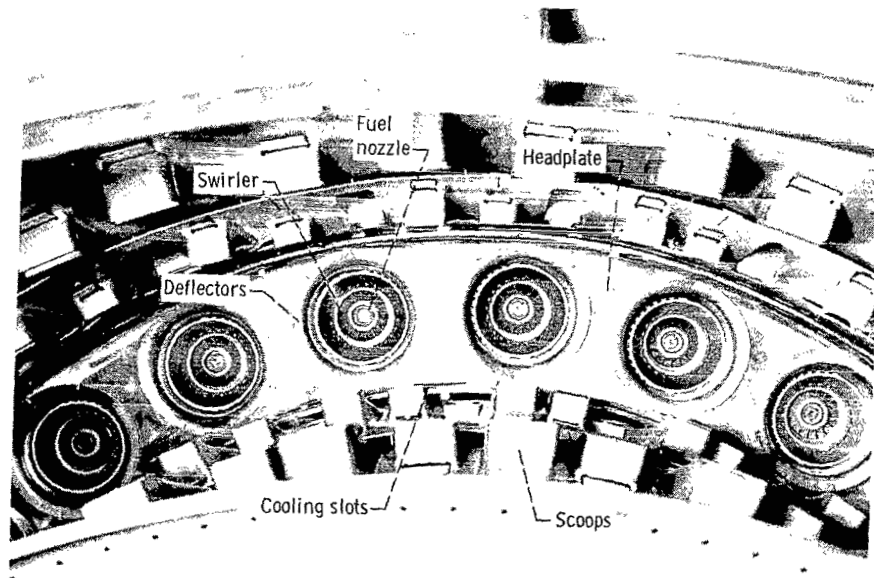
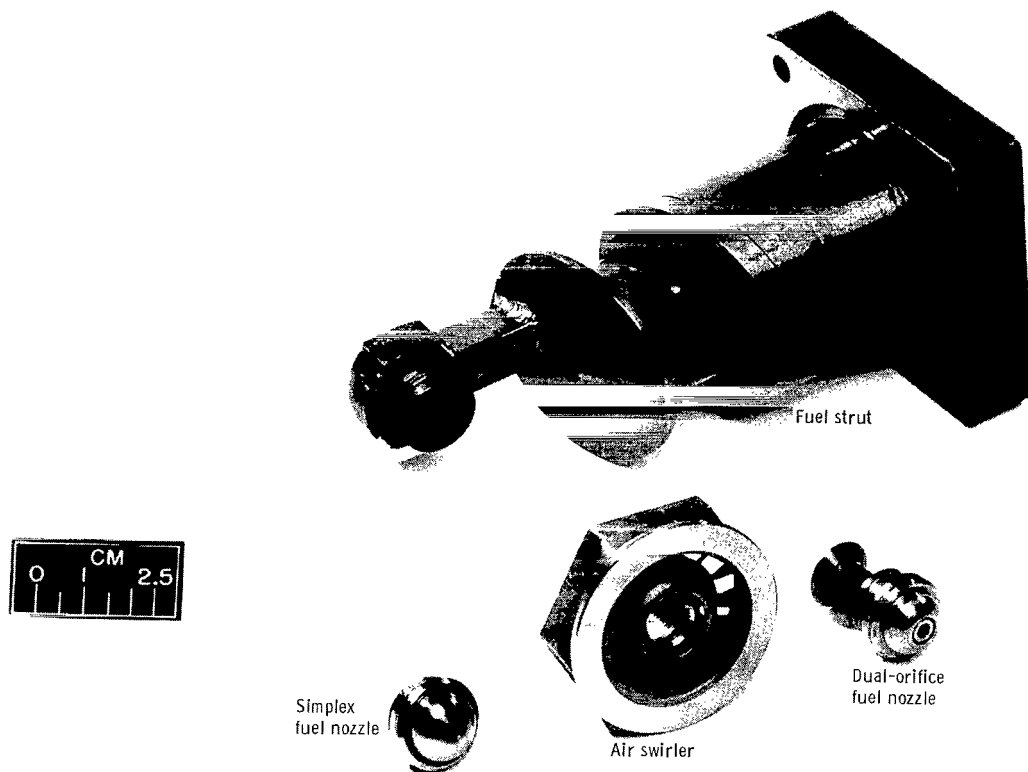


Figure 3. - Annular ram-induction combustor.



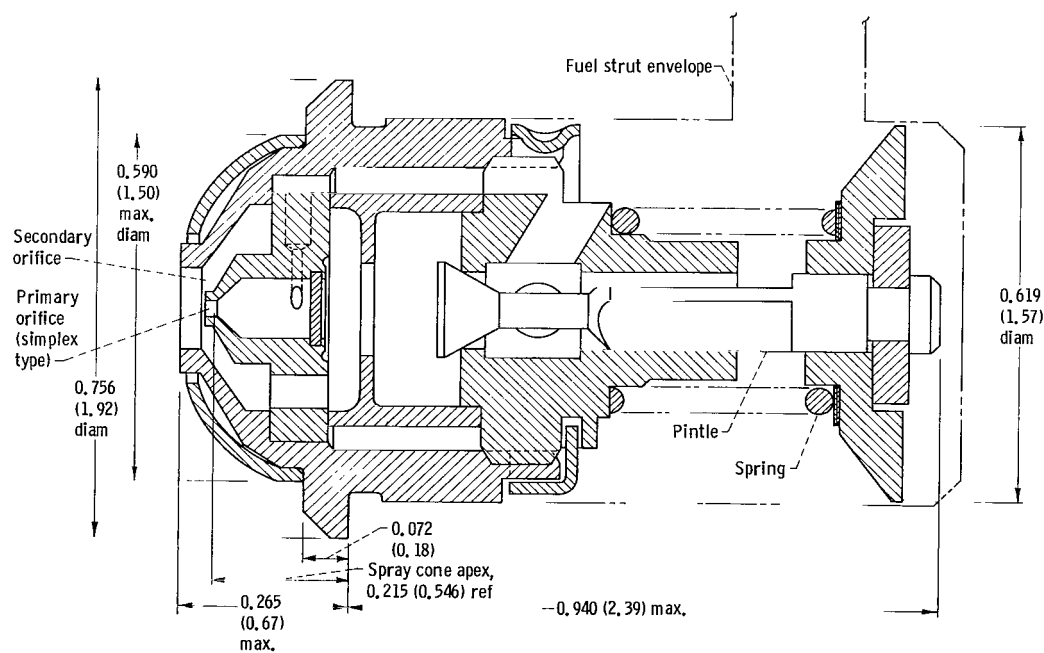
C-67-3607

(c) Viewed from downstream end.
Figure 3. - Concluded.



(a) Assembly.

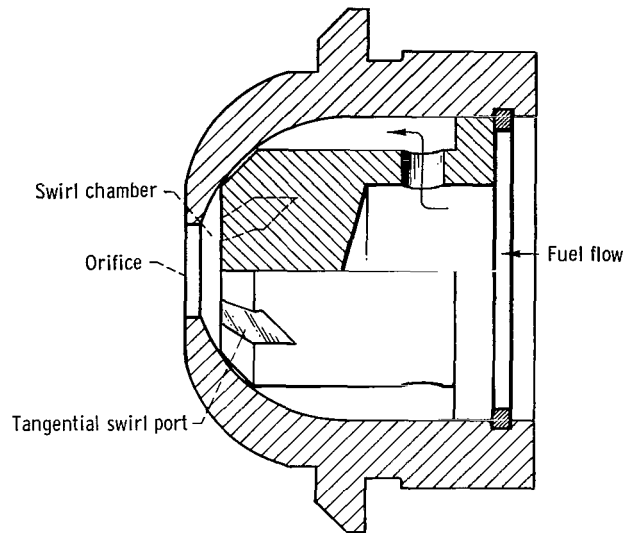
C-70-2688



(b) Cross section of dual-orifice nozzle. Dimensions are in inches (cm).

CD-10985-33

Figure 4. - Assembly and details of simplex and dual-orifice fuel nozzle assemblies.



(c) Cross section of simplex nozzle.

Figure 4. - Concluded.

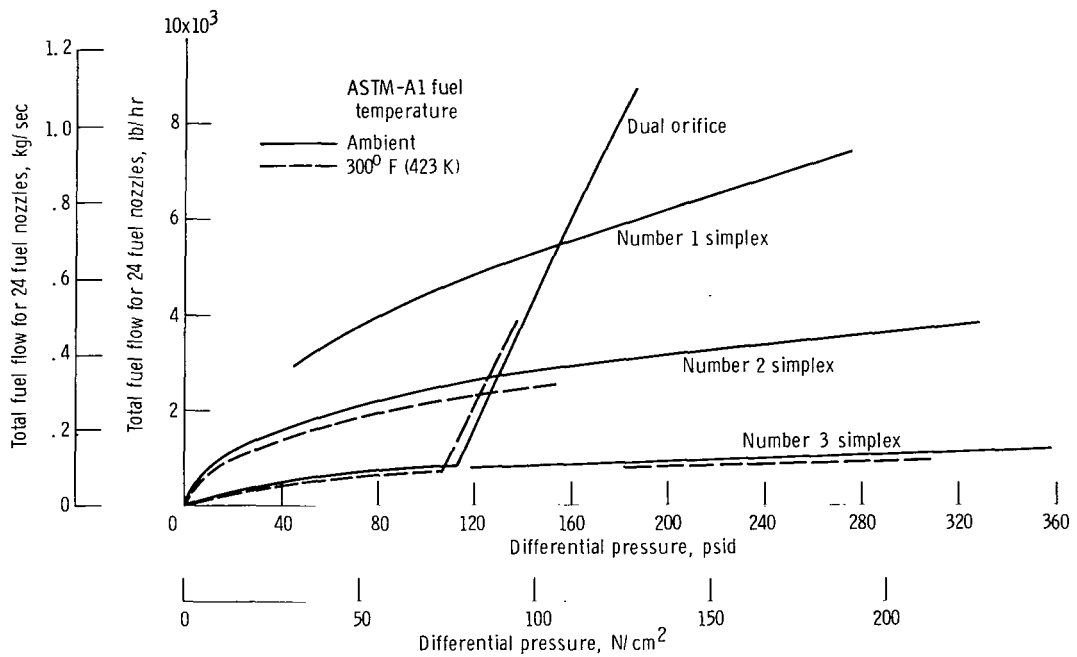
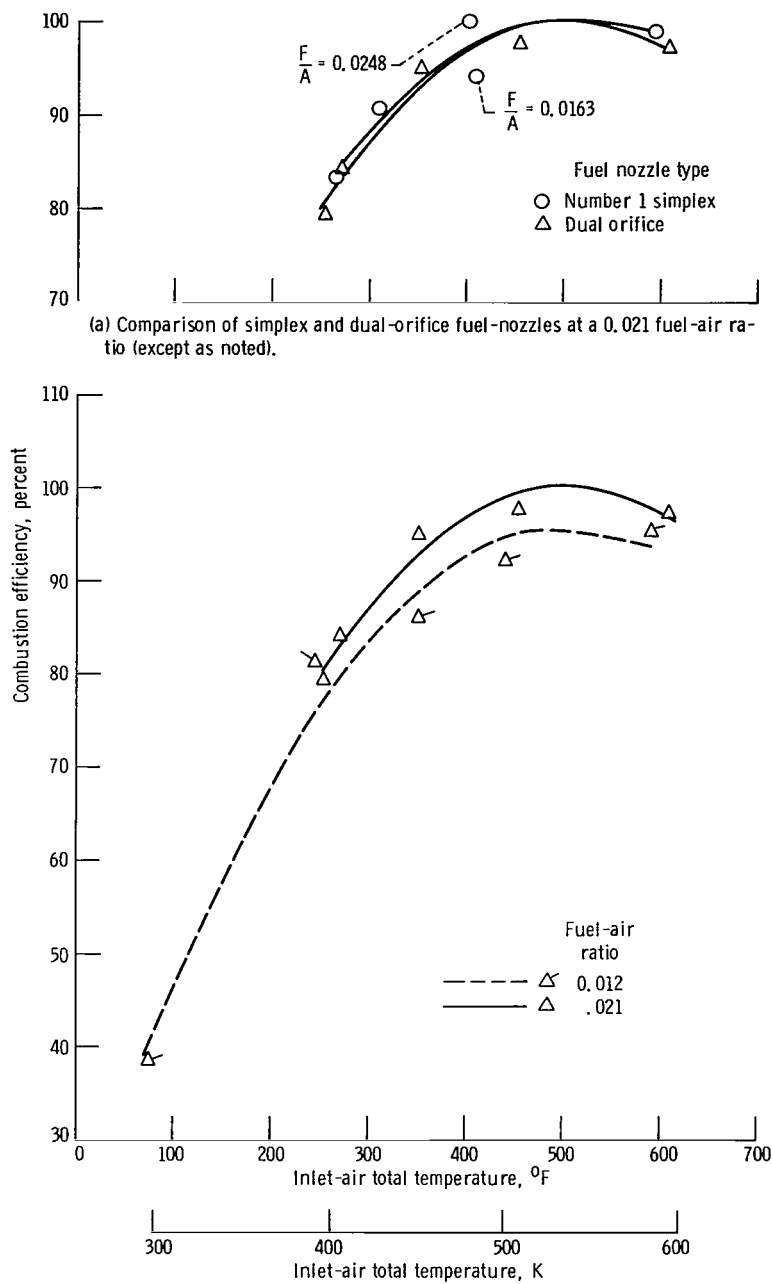
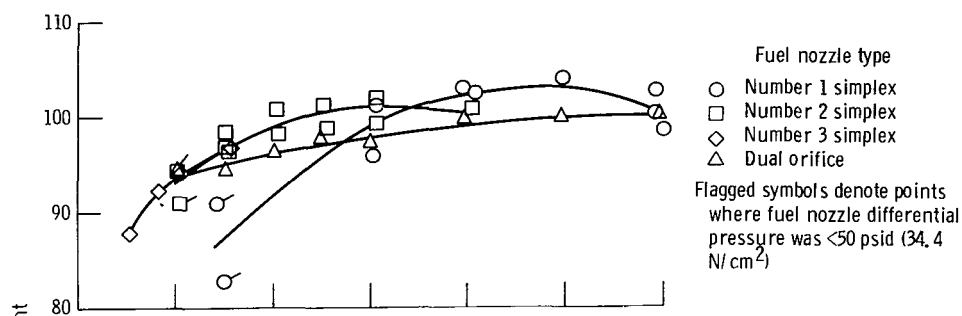


Figure 5. - Comparison of fuel flow as function of fuel nozzle differential pressure for the fuel nozzles tested using ASTM-A1 fuel.

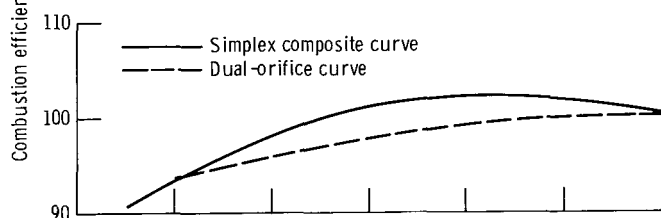


(b) Variation of combustion efficiency with fuel-air ratio using dual-orifice fuel nozzles.

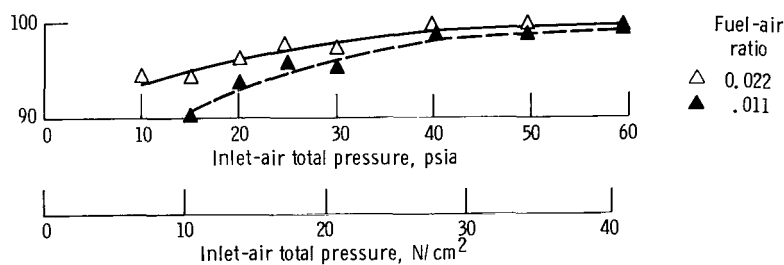
Figure 6. - Variation of combustion efficiency: with inlet-air total temperature for simplex and dual-orifice nozzles, and with fuel-air ratio for dual-orifice nozzles. Inlet total pressure, 30 psia (20.5 N/cm²); reference velocity, 150 feet per second (45.7 m/sec).



(a) Comparison of individual nozzle types at 0.022 fuel-air ratio.



(b) Composite curves of three simplex nozzles compared to dual-orifice nozzle curve (fig. 7(a)). Only points with >50-psid (34.4-N/cm²) differential pressure used in curve fit.



(c) Variation of efficiency with fuel-air ratio for dual-orifice nozzles.

Figure 7. - Variation of combustion efficiency with inlet-air total pressure. Inlet-air total temperature, 600° F (589 K); reference velocity, 150 feet per second (45.7 m/sec).

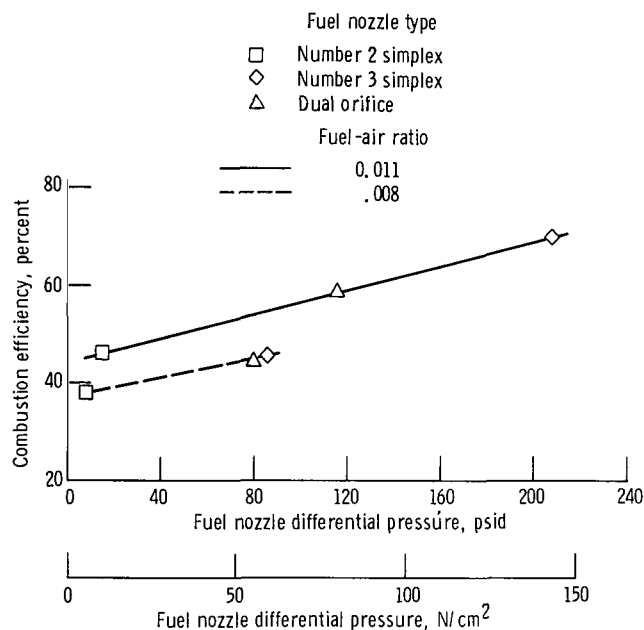


Figure 8. - Comparison of combustion efficiency as function of fuel nozzle differential pressure for simplex and dual-orifice fuel nozzles. Inlet-air conditions: total temperature, 65° F (292 K); total pressure, 18 psia (12.4 N/cm²); reference velocity, 59 feet per second (18 m/sec).

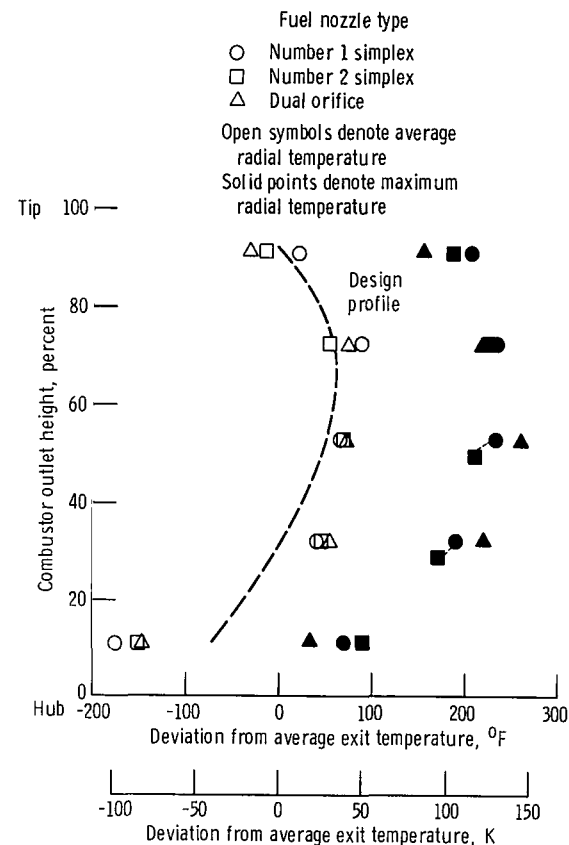
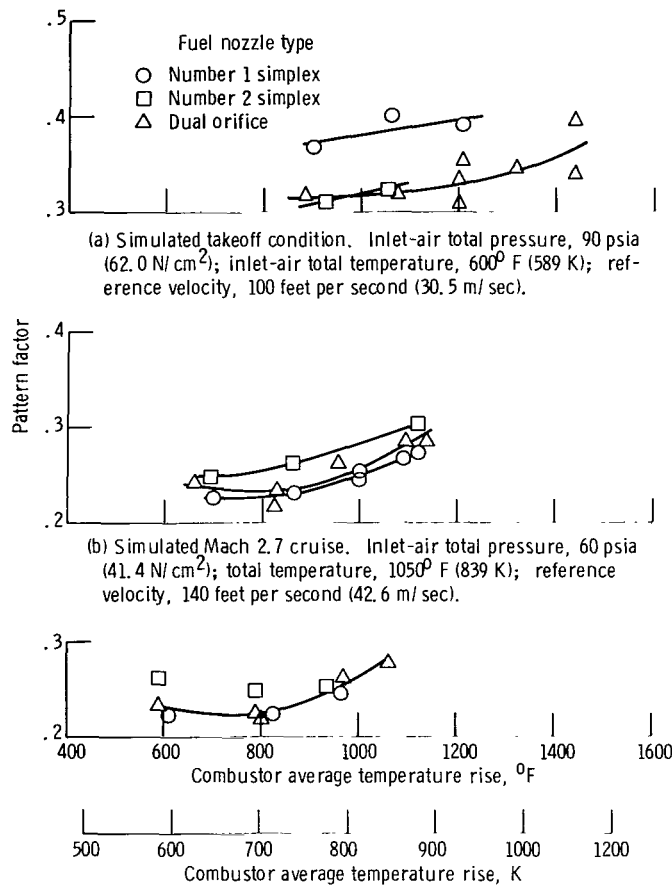


Figure 9. - Exit radial temperature profile comparing simplex and dual-orifice fuel nozzles. Inlet-air total pressure, 90 psia (62.0 N/cm²); inlet-air total temperature, 1150° F (894 K); reference velocity, 150 feet per second (45.7 m/sec); exit average temperature, 2100° F (1422 K); exit annulus height, 3.92 inches (9.95 cm).



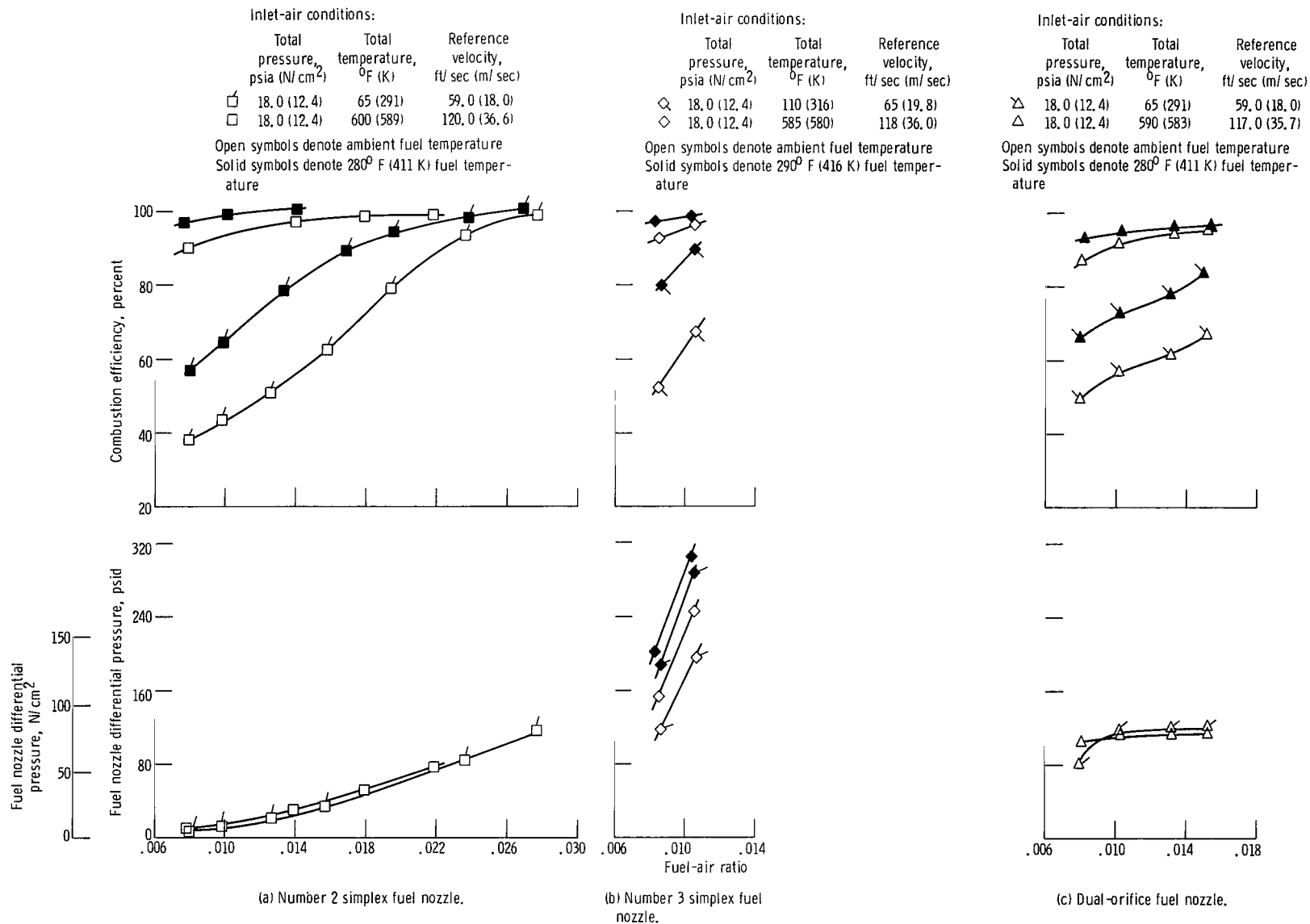


Figure 11. - Effect of 280° F (411 K) heated fuel on combustion efficiency with simplex and dual-orifice fuel nozzles.

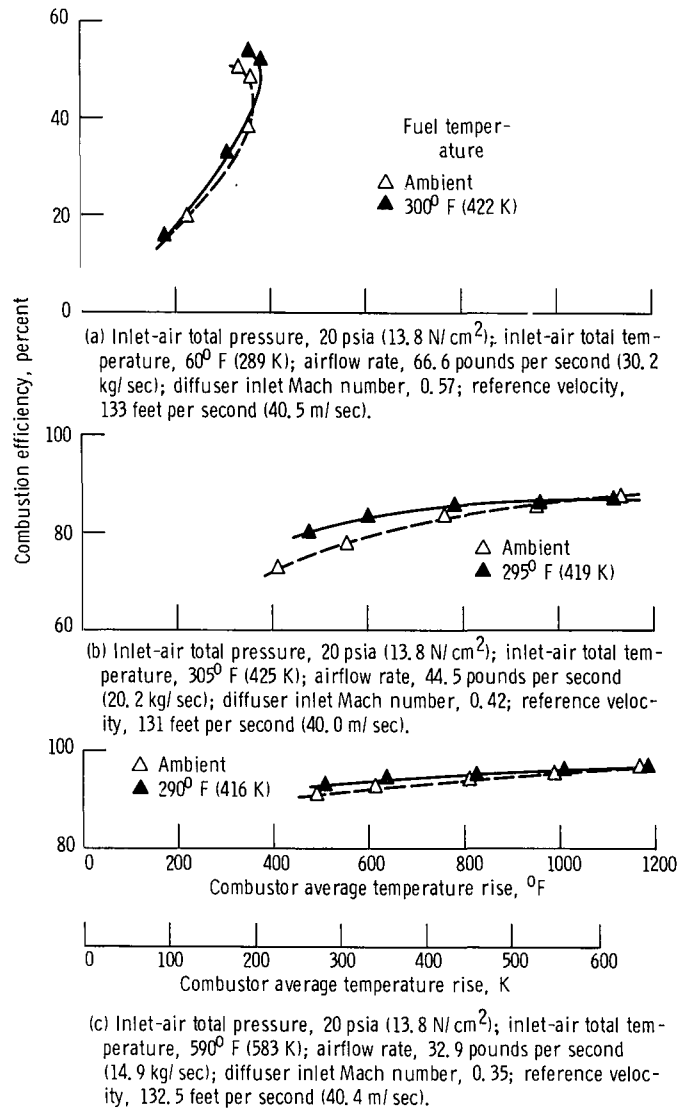


Figure 12. - Combustion efficiency as function of combustor temperature rise with dual-orifice fuel nozzles and ambient and heated fuel.

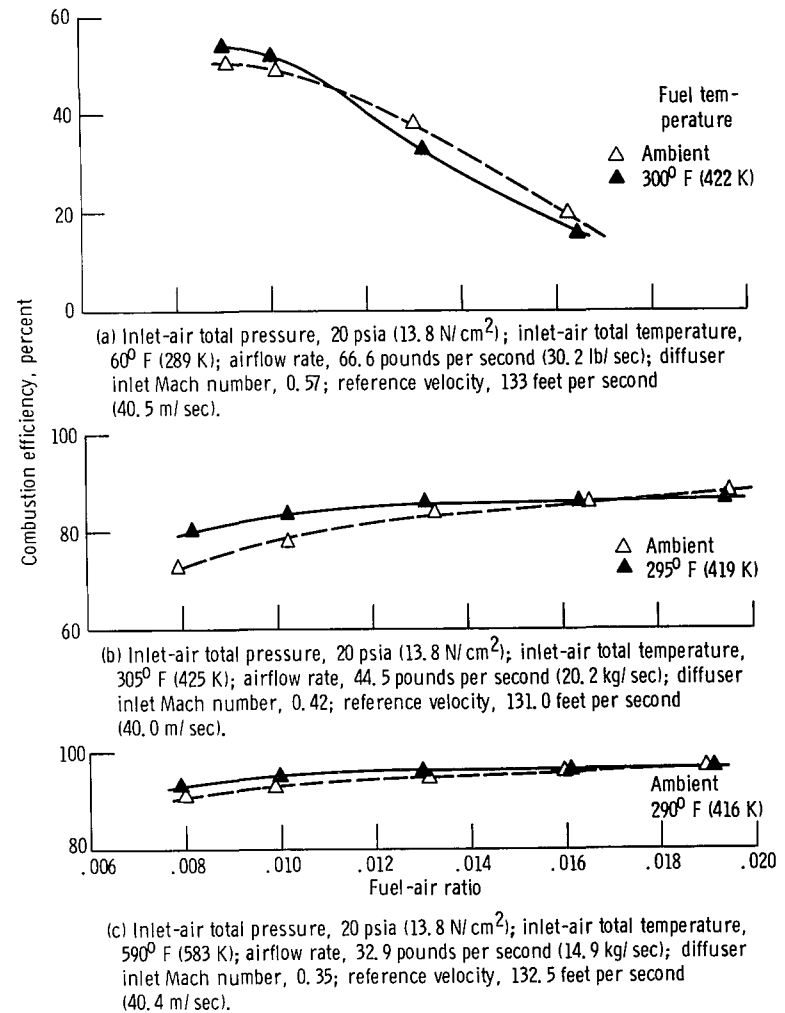
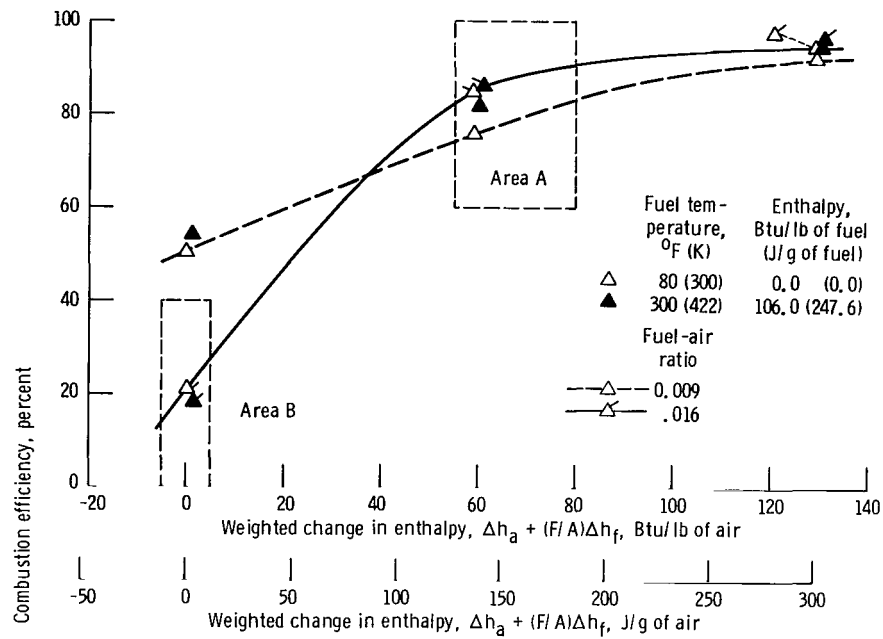
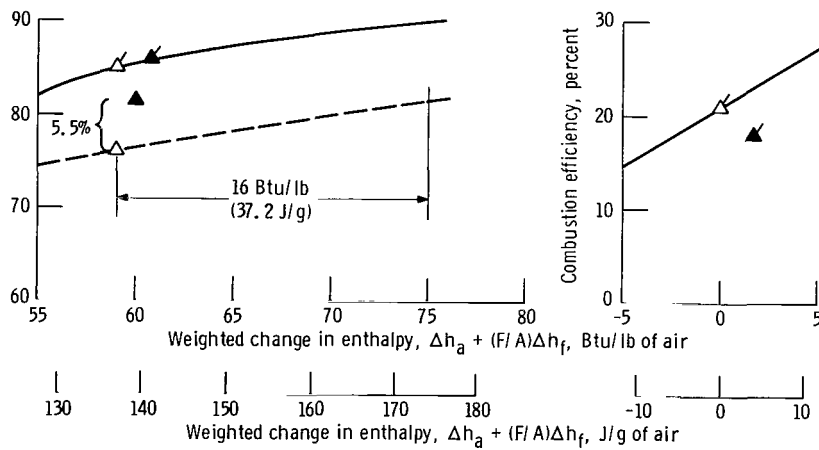


Figure 13. - Combustion efficiency as function of fuel-air ratio with dual-orifice fuel nozzles and ambient and heated fuel.



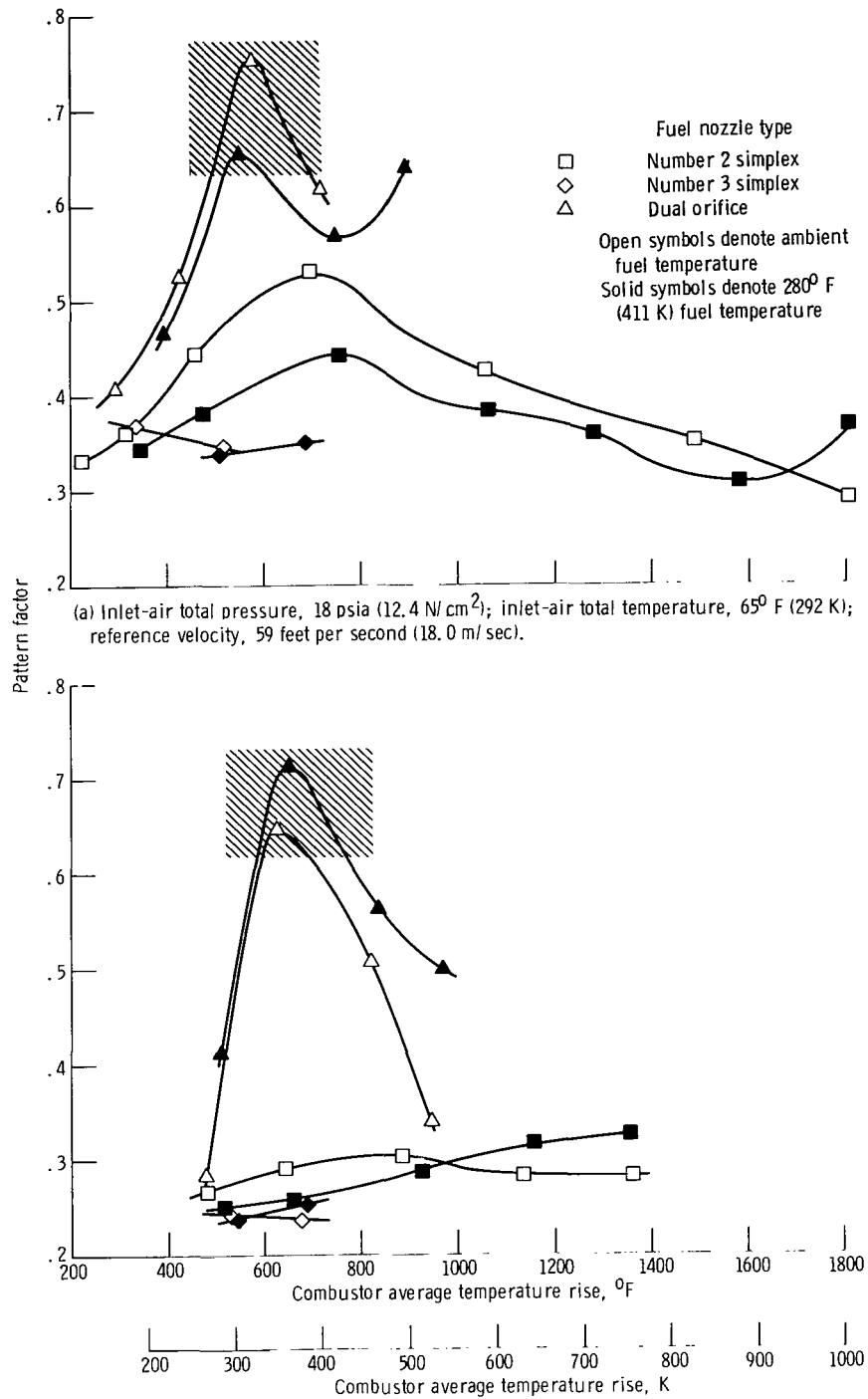
(a) Overall effect of changes in air and fuel enthalpy.



(b) Expansion of area A in figure 14(a).

(c) Expansion of area B in figure 14(a).

Figure 14. - Effect on combustion efficiency of changes in air and fuel enthalpy with dual-orifice nozzles. Change in enthalpy of air, $\Delta h_a = 0.0$ Btu per pound of air (0.0 J/g of air) at 60° F (289 K) inlet-air total temperature.



(a) Inlet-air total pressure, 18 psia (12.4 N/cm²); inlet-air total temperature, 65° F (292 K); reference velocity, 59 feet per second (18.0 m/sec).

(b) Inlet-air total pressure, 18 psia (12.4 N/cm²); inlet-air total temperature, 590° F (584 K); reference velocity, 119 feet per second (36.3 m/sec).

Figure 15. - Combustor pattern factor at off-design conditions.

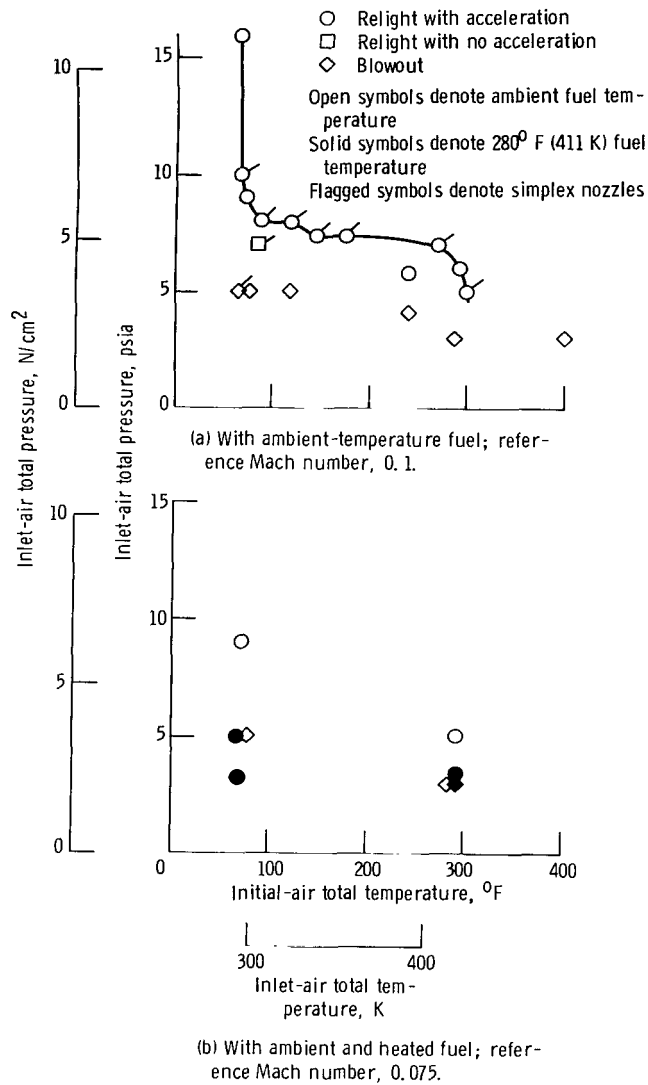


Figure 16. - Fuel nozzle relight performance at fuel-air ratio of 0.005 to 0.025 with dual-orifice nozzles and a fuel-air ratio of 0.1 with simplex nozzles.

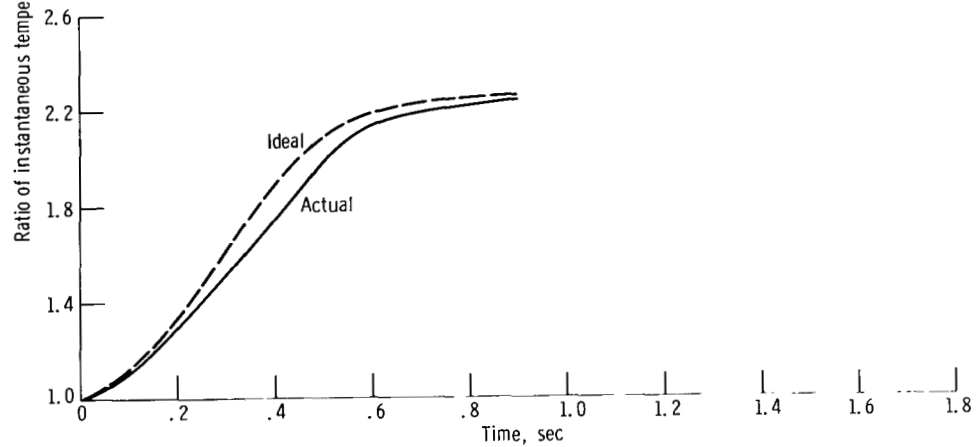
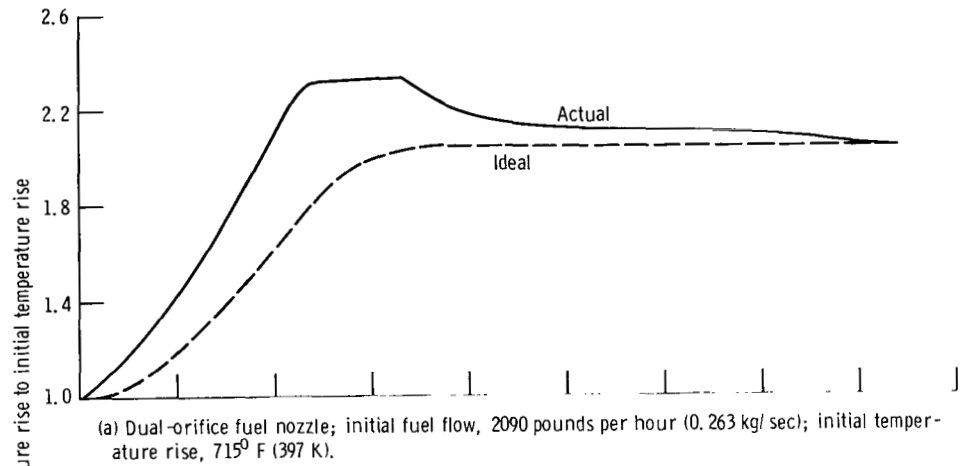


Figure 17. - Fuel burst exhaust temperature response with fast-response thermocouples. Inlet-air conditions: total pressure, 30 psia (20.7 N/cm²); total temperature, 600° F (589 K); reference velocity, 150 feet per second (45.7 m/sec).

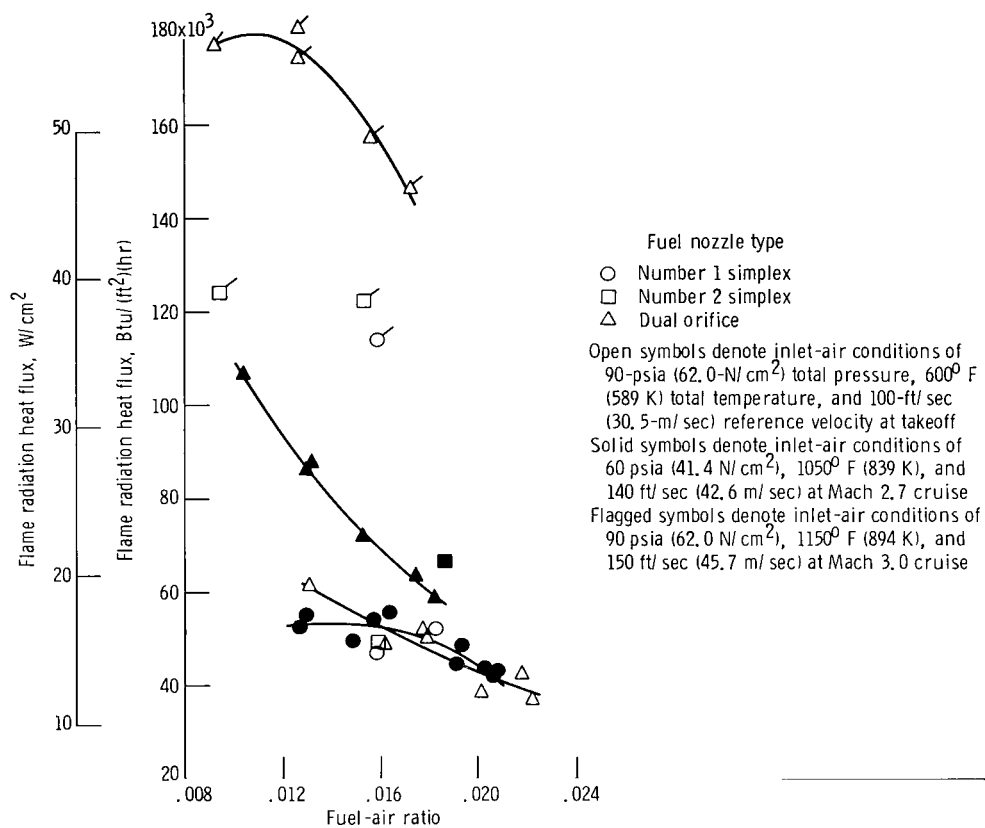


Figure 18. - Comparison of flame radiation heat flux as function of fuel-air ratio for simplex and dual-orifice fuel nozzles at simulated takeoff and Mach 2.7 and Mach 3.0 cruise conditions.

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